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The Society originated in the year 1821 as the Philosophical Society of Australasia. Its main function is the promotion of Science by: publishing results of scientific investigations in its *Journal and Proceedings*; conducting monthly meetings; awarding prizes and medals; and by liason with other scientific societies. Special meetings are held for: the *Pollock Memorial Lecture* in Physics and Mathematics, the *Liversidge Research Lecture* in Chemistry, the *Clarke Memorial Lecture* in Geology, Zoology and Botany, and the *Poggendorf Lecture* in Agricultural Science.

Membership is open to any person whose application is acceptable to the Society. Subscriptions for the Journal are also accepted. The Society welcomes, from members and non-members, manuscripts of research and review articles in all branches of science, art, literature and philosophy for publication in the *Journal and Proceedings.*

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Editorial

JAK KELLY

A WELL KNOWN MEMBER

It is not often that one of the members of The Royal Society of New South Wales has an 'International Year of ...' devoted to them. Even the Pinhole Camera only rates a day (www.pinholeday.org). However, 2009 is such a year and Charles Darwin is the member. In the vast Darwin literature little is made of his visit to Australia on his voyage in the Beagle. He is locally commemorated by having Darwin Harbour, named after him in 1839, as was the town, now the capital of Australia's Northern Territory, established there in 1911. Most people would however be unaware of his membership of our society. His gracious letter accepting membership of the RSNSW is reproduced for the first time ever in this issue as our original contribution to this year's joint celebration of his birth in February 1809 and his publication of 'On the Origin of Species' in November 1859.

He was well aware of the trouble that his ideas could cause in religious circles and in 'Species' he intentionally minimised discussion of men and apes. In vain, as it turned out. It is difficult to believe that disputes about creation and natural selection are still with us 150 years on but they are. Creationism has become Intelligent Design. This recent change of title was clearly intended to sound like a scientific subject rather than a dogma confined to religious extremists. Most countries have given up burning heretics and most of us believe in the freedom to publish what we like, subject to a few restrictions. Why worry about the teaching of ID?

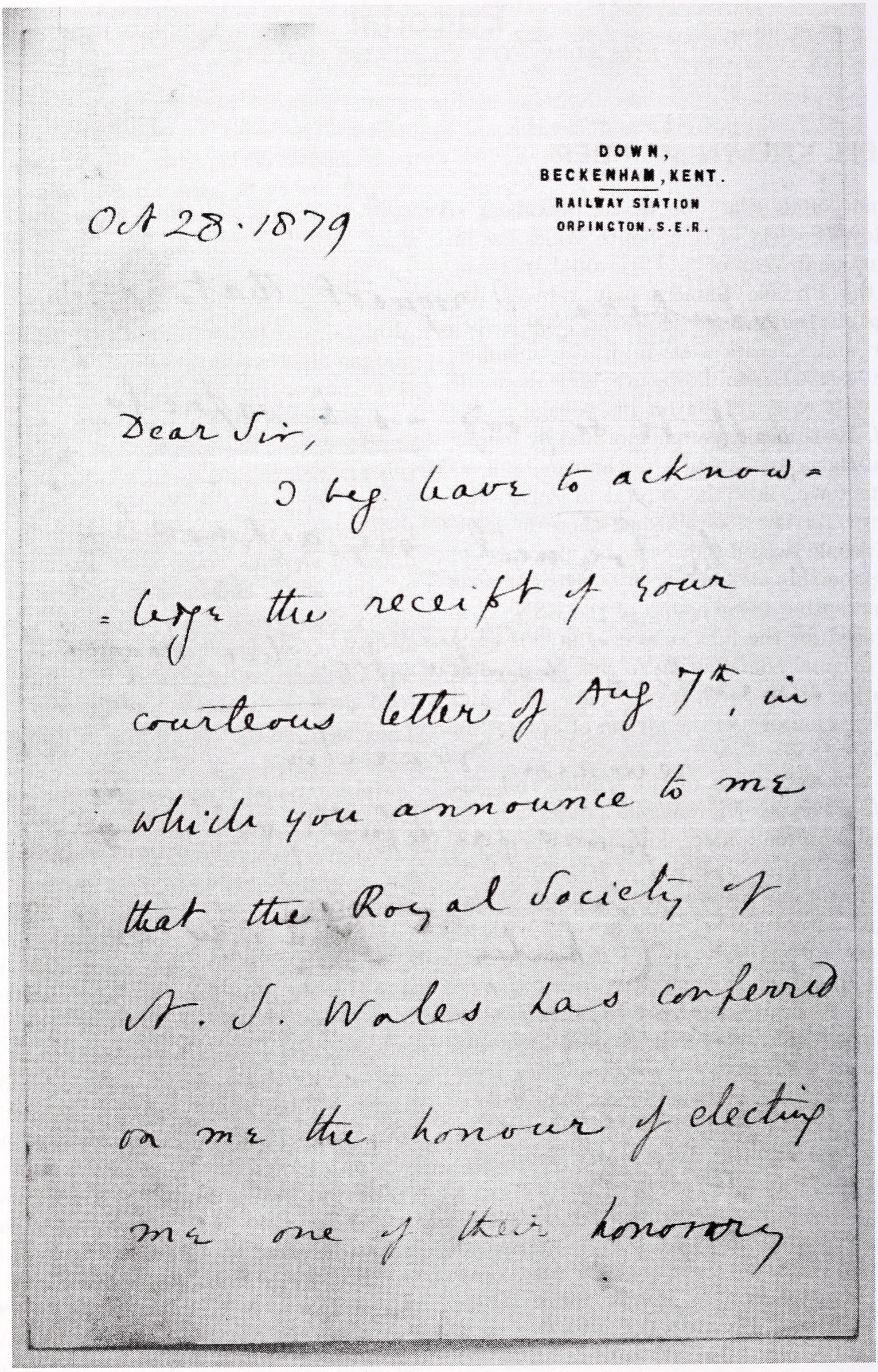
The problem is the push to have ID taught as a science. This movement is largely confined to some US states but there are a few Australian schools attempting it. If you think ID in Australia is dead, Google 'Intelligent Design in Australia'. I got 1,240,000 entries. The ID claims that the world is 6000 years old and men and dinosaurs coexisting will not stick for most students but it will waste their time and make a scientific career less likely. I am unaware of any moves to have Fred Flintstone or the Wiggles banned for supporting our coexistence with dinosaurs. As for the age of the earth, on his way to Bathurst Darwin is said to have looked out over the valleys of the Blue Mountains, which are clearly eroded from the plateau and remarked that this must have taken aeons longer than the biblical 6000 years.

The powerful US text book industry has modified some science books so as not to offend the ID people, many of whom are on state boards such as the Kansas State Board of Education. To avoid the expense of printing different versions, some of these books are used in other states and in other countries. History shows that even if most people don't believe in an idea a few determined and fanatical people can do serious damage to a society. The Nazi eugenics theories are a recent example. They were falsely claimed to be supported by Darwin's ideas.

International Years are great for publishers, perhaps they invented them, and Darwin's year is no exception. The current deluge of articles and books, for and against Darwin, is overwhelming. We are all familiar with evolution and natural selection but you may wish to know what the ID people are claiming. A useful guide is to look for any that mention Darwinism. They usually take the ID side and the term implies that evolution is an evil cult activity based on the Godless teachings of Darwin. Nobody calls Relativity Einsteinism or DNA studies Crick & Watsonism and we have Newton's Laws rather than Newtonism.

Darwin died in April 1882, not an atheist but as an agnostic far from being the evil, godless scientist the creationists claim him to be. He intended to be buried in his local church yard at Downe in Kent but he was too famous and highly regarded to be allowed such a humble ceremony. Following a state funeral he now lies near Isaac Newton in Westminster Abbey.

Jak Kelly, May 2009



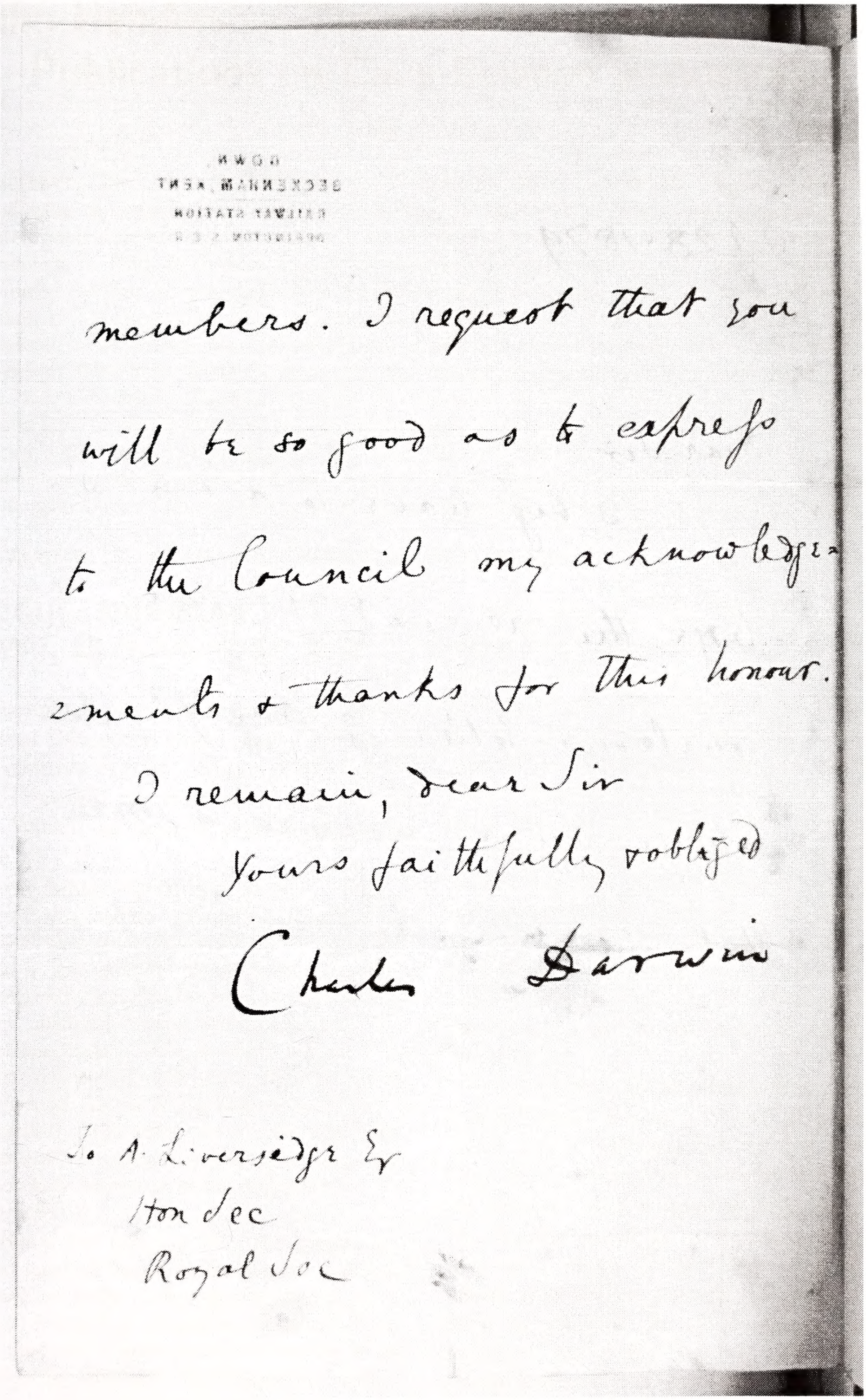
DOWN,
BECKENHAM, KENT.
RAILWAY STATION
ORPINGTON. S.E.R.

Oct 28 · 1879

Dear Sir,

I beg leave to acknow-
-ledge the receipt of your
courteous letter of Aug 7th, in
which you announce to me
that the Royal Society of
N. S. Wales has conferred
on me the honour of electing
me one of their honorary

Page 1 of Darwin's letter of 28th October 1879 to our Society accepting honorary membership.



members. I request that you
will be so good as to express
to the Council my acknowledge-
-ments & thanks for this honour.
I remain, dear Sir
Yours faithfully & obliged
Charles Darwin

To A. Liversidge Esq
Hon Sec
Royal Soc

Page 2 of Darwin's letter to our Society accepting honorary membership.

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John Henderson, Thomas Mitchell and the First Publications on Cave Science in Australia

JOHN DUNKLEY

Abstract: The work of NSW Surveyor-General Sir Thomas Mitchell in investigating and publicising the megafauna fossils at Wellington Caves is well recorded. Little known are the contemporaneous investigations carried out at Wellington and Boree (Borenore) Caves by John Henderson in 1830. Both were accomplished explorers and organisers, and between them they produced the first reports of scientific investigations of Australian caves and karst, yet in none of their publications did either acknowledge the presence or work of the other. The reasons appear to lie in personalities: Mitchell's ego, vanity and ambition, Henderson's injudicious and capricious behaviour, their common jealousy, energy, possessiveness, and intellectual rivalry, and their respective relationships with the Governor of the day, Ralph Darling. The saga throws light on why neither acknowledged the work or even presence of the other, why Mitchell tarried a day before proceeding on his Australia Felix Expedition, why his account of that expedition devoted a whole chapter to an otherwise peripheral investigation – the bones at Wellington Caves – and on the supporting role played by Assistant Surveyor John Rogers.

Keywords: John Henderson, Thomas Mitchell, Cave Science

PROLOGUE: SRINAGAR, KASHMIR, 18 NOVEMBER 1835

On 18 November 1835 the Austrian naturalist and explorer Baron von Hugel reached Srinagar on his extensive travels through that remote land, then beyond the frontiers of the British Empire. Within an hour or two of setting up his camp:

'*There shambled through the door ... a long skinny figure with a bony nose and matted red beard. His clothes were Tibetan but too dirty and tattered to be picturesque. His face was haggard and red, the skin torn to shreds by wind and cold. The Baron, normally a most courteous man, stared in amazement. "Who on earth are you?" he demanded. Unabashed, with great dignity and in a strong Scottish accent which rolled the r's the stranger replied, "You surely must have heard of Dr Henderson?" It was a fine effort from someone who cannot have spoken a word of English for several months.*'

'*The Baron had heard of John Henderson, as indeed had most of Upper India. He was the bête noir of the East India Company even before he disappeared between Ludhiana and Calcutta earlier in the year. Unfortunately no record of his indiscretions has survived. Von Hugel just says that he was such an inveterate critic of the government that he was banned all access to the press.*' (Keay 1977, p. 81)

Who was this John Henderson? In 1835 barely 20 Europeans had ever visited Srinagar. Perhaps half a dozen had crossed the Great Himalaya and Karakoram Mountains to the north. Henderson had survived a remarkable journey in search of the source of the Indus River, traversed Karakoram Pass and apparently reached Yarkand, south of Kashgar in present-day Xinjiang, China. His disguise as a fakir exposed, he was arrested several times, had escaped from Ladakh and without money or food begged his way down the Indus to Baltistan, then lost or was robbed of his journals, his baggage and his servants, and from the few extant accounts, seems to have '*gone native*' to survive.

Von Hugel and his companion Godfrey Vigne informed Henderson that in British India there was a warrant out for his arrest, and they clubbed together to enable him to continue his travels. A few days later he set off down the Jhelum heading for Balkh in Afghanistan, and after eight weeks reappeared in Lahore, where von Hugel met him again. But by then he was very ill, and he died at Ludhiana, between Lahore and Delhi on 12 March 1836. A death notice in the Agra Ukhbar (anon. 1836) regarded his talents as being '*of no common order*' and as being '*unremittingly devoted to the public good*'.

These circumstances also deprived us of an opportunity to read Henderson's own account of a singularly remarkable life, although von Hugel (1845) drew heavily on information gleaned from his journeys. Fortunately, Henderson had by then published an account of his travels in Australia, and we can piece together the activities of an accomplished pioneer in Australian cave science, investigations which, as Hoare (1968) observed, have been largely overlooked.

DRAMATIS PERSONAE

Buckland, Fitton and Mitchell

In 1824 Rev. W Buckland published his influential treatise attributing the occurrence of animal bones in caves to the Great Flood. In February 1827, having just been appointed NSW Assistant Surveyor-General in London, Thomas Mitchell made the acquaintance of both Buckland and his colleague W.H. Fitton (1780–1861), both of whom had studied Australian rocks, albeit from the collection of others (Fitton 1826). On their proposal Mitchell became a member of the Geological Society on 20 April 1827 and sought instruction and advice from them and other experts in geology, astronomy, botany, even taxidermy. Arriving in Sydney on 23 September 1827 he assumed the title of Surveyor-General upon the death of John Oxley in the following year. Quickly establishing an interest in searching for bones in Australian caves, on 13 November 1829 he explored the Grill Cave at Bungonia. He wrote that '*my chief interest in visiting there (was) to look for antediluvian remains, like those found by Mr Buckland*' (Mitchell 1838). He did not find any but his interest was whetted.

Ranken and Mitchell

Then, on 25 May 1830 the Sydney Gazette published a letter dated 21 May, signed '*L*' (attributed to Dr J.D. Lang), announcing that George Ranken of Bathurst had '*in a late excursion to Wellington Valley ... visited and explored a remarkable cave about two miles from the settlement, the existence of which had been known for a considerable time and the entrance of which is in the face of the limestone range*'. It went on to describe Ranken's discovery (in Breccia Cave) of '*a vast quantity of bones of various sizes and generally broken, some strewn on the floor of the cave, but the greater number embedded in a sort of reddish, indurated clay along its side*'.

According to Foster (1936), Mitchell had at the time been about to leave Sydney to examine progress on the Great West Road to Bathurst. Indeed, only 3 days after the Gazette's announcement he left Sydney, joined Ranken in Bathurst, and on 22 June they hastened towards Wellington[1]. By 25 June they were digging in the Breccia and Cathedral Caves, and in a third cave which, however, '*did not reveal any bones*'. On the following day they rode a hard and fruitless 45 miles to investigate a report of another large cave north of the Macquarie River. On the 27th Mitchell made his well-known survey of the Wellington bone cave, and for the next few days mixed business with intellectual pleasure. On the 29th he examined another small bone cave east of Wellington Valley, and on the following three days combined surface surveying during the day with sketching the caves at night. Packing the bones carefully, he left for Molong on 3 July, reached Bathurst on the 9th and Sydney early in August. Two weeks later Dr Lang sailed from Sydney for London with preliminary details which he duly forwarded to Robert Jameson, Regius Professor of Natural History at the University of Edinburgh, and a preliminary note appeared (Mitchell 1831).

By 13 October Mitchell had written another account and despatched it to London where it was read to the Geological Society on 13 April 1831 (though not published until 1834). He was at pains to remind readers of this earlier date in publishing his studies more accessibly in 1838, as a whole chapter in his 'Three Expeditions' book (Mitchell 1838).

1. From the time he left Sydney until he reached Bathurst on the return journey (when he corrected it with two entries for 10 July), Mitchell's journal entries show dates one day of the month later than the correct date. The dates shown in this paper are the correct calendar days of the week and month. Another discrepancy in Mitchell's dates was noted by Foster (1836): Mitchell's paper to the Geological Society (see below) was apparently dated at Sydney one day after the ship on which he despatched it had left Sydney.

Dr John Henderson

But also in July 1830, armed with some scientific credentials and also looking for bones, John Henderson appeared in Wellington, then a tiny, remote, military outpost on the frontiers of white settlement. His ideas (Henderson 1832) on cave genesis were not pursued in Hoare's (1968) paper on Henderson's time in Van Diemens Land, but were discussed briefly by Frank (1972, based on a doctoral thesis). Later, in a historical survey of scientific studies of the red earth and bones Osborne (1991) devoted a few paragraphs to his work, but his very existence apparently escaped the notice of Foster (1936), Lane & Richards (1963) and Augee (1986) in their respective comprehensive papers on Wellington. The task here is not to evaluate Henderson's science but to draw attention to a curious juxtaposition of the first two scientific studies on Australian caves.

Dr John Henderson was Surgeon to the Bengal Army, serving in Cawnpore, Aligarh, Mathura, Nemuch, Agra and elsewhere between 1815 and 1829. By his own account, he proceeded from Bengal to Van Diemens Land '*on account of my health*', arriving in Hobart on 29 August, 1829. According to the Asiatic Journal (quoted by Hoare) he left Bengal '*with shattered health, and in embarrassed circumstances*'. Unhealthy, embarrassed or otherwise, he was a whirlwind of activity during his time in Australia.

He soon recognised the need for a Society to collect and publish information peculiar to that colony, and to establish a natural history museum. Within four months he had the support of the colony's elite for a Van Diemens Land Society, been elected President, and obtained the patronage of Governor Arthur, who delivered the address at the Society's inaugural meeting on 16 January 1830. Nevertheless, within a few months he had managed to alienate powerful members of the colony, and the Society itself did not survive the year. By then Henderson was in New South Wales, having left Hobart on the Medway rather suddenly on 20 March 1830. Henderson wrote:

'*From Van Diemen's Land I proceeded to New South Wales; and continued to reside at Sydney for several months. With the view of examining the Geological formations of the country, and comparing it with Van Diemen's Land, I made another pedestrian excursion, in a westerly direction, into the interior of the country. Having arrived at Wellington, which is about 240 miles from Sydney, I remained there for some time, in order to observe the phenomena attending the deposition of those fossil remains which have lately been discovered in the Limestone Rock. Having, at the request of General Darling, prepared on his account, a collection of these for transmission to England, I addressed him a Report on the subject; and the one here published, has been prepared from my notes, which I happened to have retained in my possession.*'

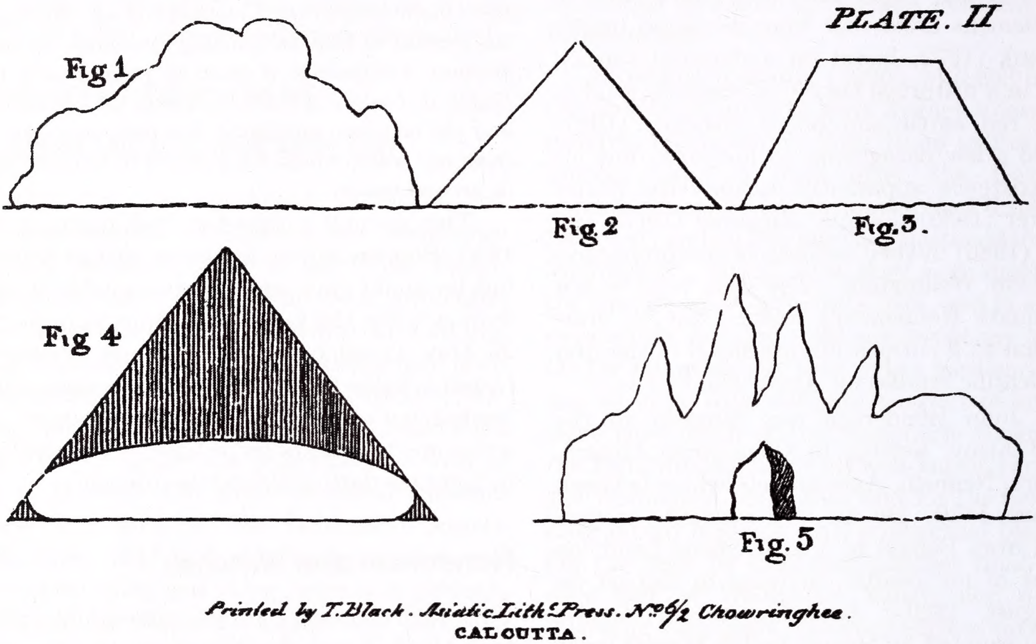
This account is dated at Wellington, 1 July 1830. Henderson was an accomplished traveller but he would have had to move quickly to leave Sydney after the Gazette account appeared on 25 May, travel to both Boree and Wellington (a remarkable journey if indeed it was entirely '*pedestrian*'), carry out some excavations and write up the results by 1 July! As we will see, in fact this date could not be correct.

Henderson and Mitchell

With such common interests, one would surmise that Mitchell and Henderson would have made a point of meeting in Sydney. It was a relatively small place and, being on leave from India, Henderson was a man of leisure if not means whose scientific credentials gained him access to the Governor, and on whose request he gathered a collection of bones '*for transmission to Doctors Fittan and Buckland of London*' (Henderson 1832, p. 109). His book devoted no less than six pages to the administration of the Surveyor-General's Department. He would therefore surely have found time for discussions with Mitchell.

Like Mitchell, Henderson must have realised the significance of the Gazette account of megafaunal fossils. They each spent time only days apart in some new discoveries in rarely visited caves near a tiny village at the very frontier of white settlement, and they each examined Boree (Borenore) caves for evidence of red earth and bones, although Mitchell's cursory visit on 4/5 July 1830 is described only in

his unpublished journal, his main investigation being delayed until 1836. In a report addressed to the Governor and reproduced in his book, Henderson produced rough sketches as Plate II, Figs. 5–12 (opp. p. 113) to illustrate his discussion of cave genesis (Figs. 8 and 9 being the first published plans of Australian caves), dating the account at Wellington the very day (1 July 1830) on which Mitchell worked in the bone cave. Yet neither mentioned the other in their respective accounts of the bones (Henderson 1832 in Calcutta; Mitchell 1838 in London) or in any other publications. It is simply not credible that they failed to meet before, during or after a sojourn in the Wellington of 1830. So, what is the explanation?



Extracts from descriptions of Henderson (1832)

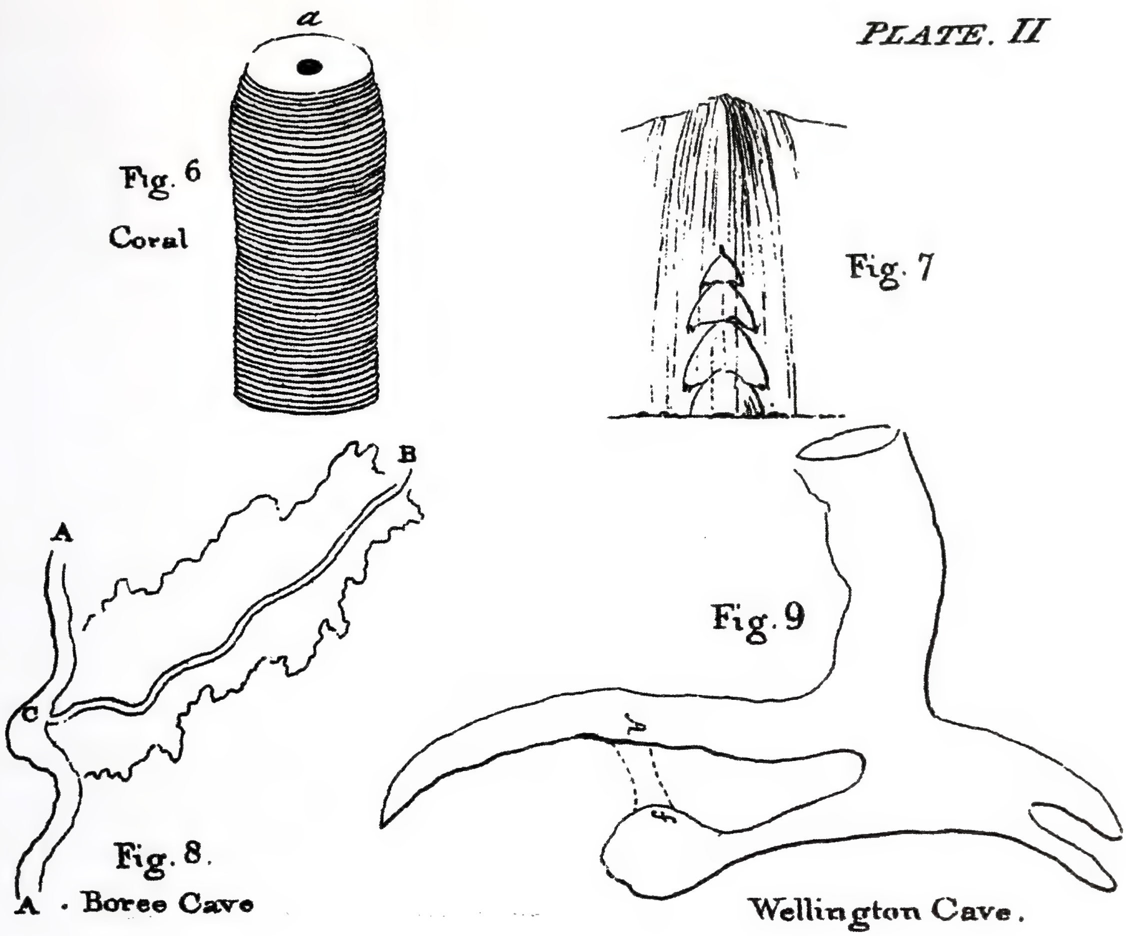
Figure 1. Where Greenstone is most silicious, without possessing an abundant proportion of Hornblend, also when it receives quantities of clay into its composition, the mountains approximate to those of Sandstone, and more particularly in the latter instance. In the previous case they are rather more detached, and evince less inclination to form ridges. Where the rock protrudes much, and assumes a granitic appearance, it likewise contains but little of the Hornblend.

Figure 2. Where the mountains rise in regular, and almost perfect cones, they generally contain a larger proportion of this mineral. Many of the above descriptions have a rock projecting from their summits, as in several of the mountains in Van Diemen's Land, and in some of those situated in the vicinity of Cox's River, in New South Wales.

Figure 3. There is also a species of abtruncated cone, a form of mountain which I several times observed in the midst of the Sandstone stratum; but had neither opportunities of visiting them, nor of learning their composition.

Figure 4. Next comes the Basalt, which in Van Diemens Land, constitutes lofty table mountains. There are also others, having crater-like summits, resembling irregularly truncated cones, and upon which those enormous crystals are observed to be extremely perfect.

Figure 5. The hills which the Limestone composes, are rarely an hundred feet above the surface of the fresh waters, whose elevation again, above the level of the ocean, is dependant on the height of the Sandstone. These hills present, generally, a smooth surface, but in certain situations, the rock protrudes in large masses, assuming sometimes, the appearance of the spires and ruins of a deserted city. This is particularly observable in the vicinity of the caves at Boree.



Printed by T. Black. Asiatic Lith. Press. No 6/2 Chowringhee.
CALCUTTA.

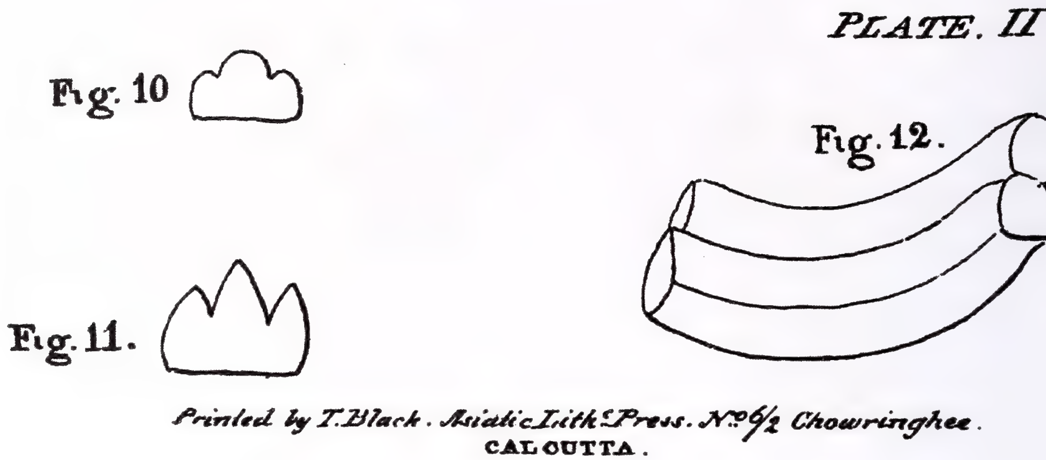
Extracts from descriptions of Henderson (1832), continued.

Figure 6. In New South Wales, the traces of marine productions are less perfect; they are, however, distinctly marked; as, for instance, in the principal cave at Boree, where large quantities of a species of Coral may be observed.

Figure 7. There are two species of Stalactics; the first or common kind, takes place from the roof, assuming the figure of a water-fall or fountain, while the place where the drop or stream falls, has a tendency to form a succession of cones, one above the other, so as to constitute a pillar; the superior cone being generally smaller than the inferior.

Figure 8. The great cave at Boree, is situated on the edge of a tolerable strong stream, which flows to the Northward, A A. Another rivulet pierces the Limestone at B, passing through it under ground for about 200 yards, after which it reappears, and joins the principal stream at C. The cave into which the water has thus found an opening, is extensive and lofty, having numerous smaller ones ramifying from each side.

Figure 9. Wellington Cave. All the bones found in this cave are either mixed with the red earth, or are enclosed in red rock ...



Extracts from descriptions of Henderson (1832), continued.

Figure 10. Has in both jaws, tricuspid teeth of the canine description, resembling rounded tridents; size perhaps equal to that of a mastiff.

Figure 11. The same; but somewhat larger; the tridents mitre-shaped; apex, sharp-pointed. Most probably, part of the remains of the Van Diemen's Land Tiger.

Figure 12. Molares teeth tubular, curved; three of them would enclose a circle the size of a penny; has more than four molares, about the size of a small dog.

Recent research has revealed that the two did in fact meet, albeit briefly, for Mitchell's unpublished journals reveal that on Monday 5 July (wrongly diarised as the 6th), two days after leaving Wellington, he wrote:

'*On our arrival at Molong we found a Dr Henderson waiting for us – by the bye we found it difficult to cross the river which I believe is the Bell or a branch of it – the other at Boree with the bridge empties into the Lachlan. Dr Henderson seemed a very odd personage – he walked with a black boy. He said there was no granite nor any primitive rock in the country – that he was making a section of the strata. He was going to Wellington and wished to have gone 70 miles further – he rode on drays to carry him over the rivers. He read a book of his to Rankin and on financial arrangements and said he was come from Van Diemens Land where he had done much good, to set us right too, for we were all wrong.*'

The implication is that they were not previously acquainted, but no doubt Mitchell described his load of bones from Wellington and mentioned that he had come from Boree that very day, probably only emboldening Henderson, who in turn quite likely mentioned his permission from the Governor to collect bones. Henderson left next morning for Wellington with a Mr Walker, visiting Boree on his return journey, while Ranken left for Bathurst. Mitchell says he continued completing the plan of Wellington Valley before setting out the following day for Bathurst and Sydney with the bones. No wonder he needed a rest day: he had been in caves on 12 of the previous 14 days, ridden about 250km, and diarised that '*I was much inconvenienced by the boils in riding back*' (to Molong the previous day)!

We are now able to examine the motives of the players. Perhaps, upon learning of the cave discoveries Mitchell used the power of his office to decide he urgently needed to inspect the road to Bathurst, visit Wellington to plan the survey, and simultaneously seize the opportunity to boost his profile and credentials in the home country. He may not at that stage have been acquainted with Henderson, but later in the saga, quite probably Mitchell's ego did not allow him to associate or be identified with someone who he privately described as '*an odd personage*', who had obtained vice-regal support in collecting bones, who had designs on exploring country he wanted to examine for himself, who had confided those intentions in and sought support from the Governor, who had criticised his administration, and whose views about the bones were at odds with his own anyway.

Darling, Mitchell and Henderson

Governor Darling appears to have played off one protagonist against the other, in particular using Henderson as a foil against Mitchell. He had approved collection of bones by Henderson, probably knew or suspected that Mitchell's journey beyond an inspection of the road to Bathurst would involve bone collection, and may well have been instrumental in Henderson's deprecation both of the professionalism of the Surveyor-General's Department and specifically of the wisdom of expending public money on the road to Bathurst.

It is a matter of record that he and Mitchell were never on good terms. He had thwarted Mitchell's plan for an expedition to the north or west coast of Australia. For his part, Mitchell had written directly to Colonial Secretary Hay in London (a breach of protocol scarcely endearing him to Darling) on the day before the Sydney Gazette item (i.e. 24 May, 1830), seeking permission for such an expedition i.e. beyond Wellington. Then, shortly after Mitchell's return to Sydney in July, Darling complained to Colonial Secretary Hay that: '*The attention of the Surveyor-General, who seems injudiciously anxious to do everything himself, is so much occupied in the Road Branch, that, to say the least, the more important duties of his Office (i.e. the trigonometrical survey) cannot be attended to in the same degree as if that Department had not been placed under his superintendence*'. He was often critical of Mitchell's tardiness in producing the map (e.g. letter to the Under Secretary for the Colonies on 28 May, 1831) (Historical Records of Australia XVI, p. 222), and within months he attempted to strip Mitchell of responsibility for Roads and Bridges and to secure his dismissal. But by then Darling had himself been recalled, leaving in October 1831.

Upon returning to Sydney, Henderson also unsuccessfully petitioned the Governor to assist him in an endeavour to travel (at his own expense) on explorations beyond the Nineteen Counties and in particular west of Wellington (Henderson 1832, pp. ix–xi). Rebuffed, he returned to Wellington anyway, and without map, compass or local guide, travelled east through unexplored country to the Hunter Valley, accompanied only by '*a servant, a native of Hindostan*'.

Rogers, Mitchell, Ranken and the Australia Felix Expedition

There are some other clues explaining Mitchell's actions and motives. On 24 July 1830 (while still in Bathurst on the return journey) he wrote recalling Assistant Surveyor John Rogers from uncompleted work in the Goulburn River area and despatched him to Bathurst, Molong and Wellington, inter alia with specific instructions (given also to other surveyors) to mark occurrences of limestone: '*You will also note particularly where limestone occurs in all your Survey and this you will tint on your Map by a grey made by mixing blue and red together shewing something like the extent of the limestone rock*' (Mitchell to Rogers on 24/7/1830, Rogers 1830).

Rogers' notebooks reveal on September 9th: '*Plotting – Sent two Men to dig for Bones at the Caves near Wellington Valley NB informed that there are other and more extensive caves in the neighbourhood of Canobolas not yet visited by persons collecting therefrom.*' Although they are not in fact more extensive than Wellington, this could only refer to Boree (i.e. Borenore) Caves, a surmise supported by the fact that despite this area not being in his new brief, Rogers went there on 28 September, 30 November and again on 25 and 26 December, 1830. However other than for his '*cursory visit*' on 4/5 July 1830, Mitchell's investigations did not occur until the very beginning of his Australia Felix expedition (Mitchell 1838, pp. 6–7). On 18 March, 1836, one day after leaving Orange, he stopped at Borenore, diarising that the time for cave exploration was available '*as it was necessary to grind some wheat with hand-mills, to make up our supply of flour*'. This is curious: surely an expedition would not depart before preparing its flour supplies? Fortuitously, George Ranken was at hand, having accompanied him from Bathurst and together they spent a full day in exploration. It is difficult to escape the inference that Ranken, who was not part of the expedition and lived over 100km away, had been asked to come specifically to help in the

cave exploration, and that on a pretext, the expedition was delayed a day to enable them to do so. Mitchell wrote:

'The limestone occurs chiefly in the sides of vallies (sic) in different places, and contains probably many unexplored caves. ... I had long been anxious to extend my researches for fossil bones among these caves, having discovered during a cursory visit to them some years before, that many interesting remains of the early race of animals in Australia were to be found in the deep crevices and caverns of the limestone rock. ... I was anxious to ascertain, by a more extensive examination of the limestone country, whether the caves containing the osseous breccia, presented here similar characteristics to those I had observed in Wellington Valley. ... It may be imagined what a vast field for such interesting researches remains still unexplored in that district, where limestone occurs in such abundance.'

Neither Mitchell nor Henderson was particularly qualified academically to study the deposits. Mitchell was a surveyor with some geological training; Henderson a surgeon whose writings reveal a well-educated man and a sound facility with zoological nomenclature. Both had wide-ranging intellectual interests of that peculiarly nineteenth-century kind, although Mitchell was the more accomplished polymath. Mitchell had advantages to posterity in that he foreshadowed modern, post-Darwinian thinking, and had the connections to promote those views more widely. Indeed, Darwin visited Sydney in 1836 and Mitchell continued correspondence, meeting him in London the following year. Henderson attributed the distribution of bones to a flood sweeping down from Canobolas, past Boree and strengthening towards Wellington, and predicted the discovery of bones along the intervening river-beds. Not exactly the Biblical Deluge, but he was evidently influenced more strongly than Mitchell by Buckland's recently published treatise. Mitchell also suggested inundation of the caves, but subsequent to rather than a cause of the distribution of bones.

Characterising Mitchell as a '*colonial scientist*', secondary to those in the home country, whose earnest goal was to have his full account published in the Transactions of the Geological Society, Oldroyd (2007) speculated that Buckland may have thwarted this because '*modern Australian forms might not have been pleasing to those who had in mind universal catastrophes followed by creation of new forms.*' Indeed, in a letter to Ranken on 24 July 1833 Mitchell wrote: '*I understand Buckland's nose is put completely out of joint by the bones from Australia ... and I have now heard from the best authority that the fact of their fossil bones not belonging to animals similar to those now existing has worked a great change in all their learned speculating on such subjects at home.*'

Mitchell's account is certainly more intellectually rigorous while his protagonist appears out of his depth. He had the benefit of peer review (e.g. from Professors Jameson and Owen in London, and from Lang who nevertheless remained anonymous, perhaps to avoid becoming embroiled in controversy). He had astutely arranged for Lang to convey the preliminary account to London and for a paper to be read before the Geological Society of London in 1831 (though published only in abstract), while Henderson had to be content with an obscure missionary press in Calcutta without benefit of peer review. His maps were, of course, professionally executed whereas Henderson's were no more than rough sketches. His discoveries were referred to in Lyell's great text (1833).

Just what happened to Henderson's bones is unclear. He reported to Darling that several boxes of bones '*are now ready for transmission to Doctors Fittan and Buckland of London*', but neither records receiving them. Owen (1877) does not mention Henderson in his seminal work, writing in the preface: '*The exploration of ossiferous caves has hitherto been limited to those originally discovered by Sir Thomas Mitchell.*' If Mitchell was merely a '*colonial scientist*', Henderson must have ranked lower!

Finally, this saga throws additional light on Mitchell's motive for stopping at Borenore and for devoting an entire chapter of his 'Three Expeditions' book to the Wellington bones. It was not simply intellectual curiosity. Stung by Henderson's publication four years earlier and by a failure to have his own account published fully in the scientific community, he must have determined that his views would prevail in

a widely acclaimed volume that undoubtedly reached a wider audience.

HENDERSON IN RETROSPECT

It would be easy to dismiss Henderson as an opportunistic dilettante in matters paleontological, but then so was his nemesis, although as we have seen, Mitchell had at least sought advice and instruction from other experts and displayed a more disciplined mind. Henderson founded Van Diemens Land's first scientific society, which was second in Australia only to the Royal Society of NSW. He published a number of scientific papers catalogued by the Royal Society of London (1869). Reproduced in his Observations, his proposals for a new system of zoological nomenclature received the attention of the Institute of France in Paris, and were '*clearly not a result of uninformed amateur thinking*' (Hoare 1968, p. 18). Typically, he considered it futile to submit his ideas to the Royal Society in London, a body with '*a strong disinclination to change*'.

In a busy life in India he engaged in mercantile pursuits, attempted cotton improvement in Upper India, tried (unsuccessfully) to introduce the spinning jenny into Aligarh, and speculated (again without success) in the growing of indigo and other crops. Upon his return from New South Wales early in 1831, he apparently joined the East India Company, and variously in Agra and Ludhiana, founded a medical and public library (and, it seems, the Agra Bank), reorganised an orphan school, started a cornmill, tried to form a horticultural society, and ran an English, Persian and Hindi newspaper. We have already seen that he was an accomplished, if somewhat eccentric traveller.

A creative and insightful thinker, clearly possessed of considerable organisational skills and a finely honed mind for theoretical systems of zoological classification, Henderson's weakness was an inability to carry his numerous plans through to fruition. Notwithstanding great perseverance, determination and fortitude bordering on asceticism, he presents less as an explorer, more as a resourceful, observant, determined and adventurous traveller. Possibly he felt spurned by or resentful towards Mitchell, but this does not excuse his shameless opportunism in dating a subsequently published report to the Governor before he had even reached Wellington. A contemporary reviewer (West 1852) described him as censorious and dogmatic, a judgment consistent with Henderson's deprecation of the Surveyor-General's Department, while the writer of his death notice (anon. 1836) felt that he was restless by nature and that his thoughts and schemes '*flowed too quick upon him to allow him to think as soundly as rapidly*'. Hoare concluded that he sought consolation in his failures by turning immediately to new projects and travels.

As we have seen, Henderson's report to Darling could not have been written by the date claimed by him (i.e. 1 July 1830). Putting this aside, we don't know whether that report reached the Governor first, or even when he returned to Sydney. In view of Darling's displeasure with Mitchell's tardiness in his official duties, there may not have been one from Mitchell; certainly he does not mention any. Henderson published the first detailed account, so there is a case for crediting him with Australia's first comprehensive paper on cave science. For all his shortcomings, he has three other noteworthy claims on the history of karst science in this country. His sketches of Boree and Wellington Caves were the first published plans of Australian caves, and he was first to comment, albeit in a rambling manner, on the supposed effects of fire or heat on limestone, erroneously attributing at least some of the product to volcanic activity. Finally, he appears to have been the first to sketch and write about karst topography: '*These (limestone) hills present, generally, a smooth surface, but in certain situations, the rock protrudes in large masses, assuming sometimes, the appearance of the spires and ruins of a deserted city. This is particularly observable in the vicinity of the caves at Boree*'.

There is one last curious coincidence in this saga. Pursuing his botanical interests, von Hugel came to Australia in 1834, visited Bungonia Caves, met Ranken in Bathurst and was deterred from proceeding to Wellington only by the distance and the apparently '*uninteresting*

flora' in between (von Hugel 1834). No doubt he and Henderson had much to talk about at that remarkable meeting in Srinagar the following year!

EPILOGUE

Within a year of the discoveries at Wellington, Darling had been dismissed, Henderson had returned to India and only Mitchell was left standing, his reputation intact. Indeed it was considerably enhanced when he finally completed and published his great Map of the Colony in 1834 (Mitchell 1834b, Beaver 1952), and after the Australia Felix expedition of 1836 and his 1838 book his unassailable stature led directly to a knighthood. Perhaps Mitchell had seized an opportunity and contrived to take advantage of it immediately, rather than being fortuitously '*about to journey to the Western Districts*' as Foster assumed. A long-awaited opportunity was presented, his motive had elements of ambition as well as almost obsessive intellectual curiosity, his means was the power of his office, and everything was driven by his energy and ego. Certainly his legacy was the fostering of scientific interest in Australian vertebrate fauna in the mid-nineteenth century.

Here, it seems, were not only the first scientific studies, but a pioneering example of intellectual rivalry, vanity, jealousy and possessiveness of a kind not unknown to later generations of speleologists and scientists! Here also was a classic example of the manner in which political patronage and rampant egos operated to the detriment of a common interest in science, and where overlooked, overshadowed and unremarked players such as Henderson and Rogers are forgotten. As Branagan (1992) noted in his overview of a symposium on aspects of the life of Mitchell and Sir Richard Owen, '*There would be little of interest in a bloodless history of science*'!

Henderson deserves a rightful place in the history of cave science, and indeed of science generally in Australia. Without Mitchell, his flawed but perceptive writings – remarkable for their time – might now be widely accepted as the pioneering scientific publication on caves and karst in Australia, and recognised in a succession of studies of the Wellington bones. As it is, Henderson was memorialised only in his book, a plaque on the Isle of Chenars in Dal Lake, Srinagar (which apparently was destroyed by 1850), and an obituary in the Agra Ukhbar (anon.1836). Both recognised the significance of the bones, and both moved swiftly and determinedly to pursue their legacy. But history belongs to the victor. Major Mitchell was closer to the truth, his writings attracted more influential attention, he rose to greater honours, and in the process he became Australia's first speleologist.

ACKNOWLEDGMENTS

Earlier versions of this paper were published in the body of more comprehensive reviews (Dunkley 2002, 2003) of cave history in Australia. I am indebted to Dr Anna Binnie for encouraging me to publish more widely the saga relating to Henderson, Mitchell and Darling. I thank Dr David Branagan for comments on an earlier draft and for further encouraging publication of this paper, even though it has taken eight years to fruition. Finally, my thanks to Dr Michael Lake for his editorial patience.

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For Further Consideration: Mr James Dunlop, Esq.

SHARON RUTLEDGE

Abstract: James Dunlop submitted a paper to the Royal Society of London in 1833–34. The archives of the Philosophical Transactions of the Royal Society record an abstract for this work but the manuscript itself was not published. The original paper has now been located within the extensive archives of the Royal Society. The main content of this document entailed his 'at sea' magnetic research from his second voyage to New South Wales (NSW). He extended the study with further 'on land' data collection particularly from Parramatta and Sydney. The following paper briefly outlines the interest in the 19th century for magnetic observations and goes on to examine aspects of Dunlop's unpublished manuscript. An overview of James Dunlop's role in Australian scientific history and his lack of recognition are also discussed.

Keywords: Astronomy, Brisbane, Dip Needle, Dunlop, Magnetic Observation, Parramatta Observatory

INTRODUCTION

It is June 1831 and the ship 'Mary' is at anchor below Woolwich equipped for a voyage to the Australian colonies. The occupant of the '*stern cabin in the poop on the harbour side*' (Dunlop 1834a, p. 1), James Dunlop, shown in Figure 1, is preparing to undertake '*the most extensive uninterrupted series* [of magnetic observations] *...extending over the Earths surface about 180 Degrees in Longitude and 100 Degrees in Latitude*' (Dunlop 1834a, p. 1).

Suspended from his cabin roof is a magnetic needle device, which will remain fixed in this position throughout the long journey. Dunlop's trunks are also packed and stored in a manner to ensure their contents cannot affect the magnetic apparatus.

DUNLOP'S EARLY YEARS

On October 31st 1793, the son of an Ayrshire weaver was born in the village of Dalry, Scotland. Young James working in a Beith thread factory had a mechanical gift. At the age of seventeen, '*he was constructing lathes and telescopes and casting reflectors for himself*' (Service 1890, p. 135). Sir Thomas Brisbane, the newly appointed Governor of NSW, had determined to build a private observatory in that colony. Sir Thomas, also from Ayrshire, became aware of Dunlop's skills. Deciding these abilities would be useful in the distant settlement, he engaged Dunlop's services to maintain the delicate astronomical instruments. Although Brisbane was himself an avid astronomer, he understood the Vice-Regal role in NSW would force limitations on his personal involvement in the new observatory. Sir Thomas therefore also employed a German mathematician and astronomer Christian Carl Ludwig Rümker as an assistant.

James Dunlop, with his wife Jane, accompanied Governor Brisbane and Carl Rümker to the colony of NSW arriving at Port Jackson on November 7th 1821. Upon completion of the observatory built near Government House Parramatta, the mammoth task of '*cataloging* [sic] *all stars of 8th magnitude or brighter south of declination -33*' (Cozens & White 2001, p. 113) commenced on May 2nd 1822. Following Rümker's acrimonious departure from Parramatta, in 1823, Dunlop recorded the bulk of the observations and he completed a catalogue of 7385 stars by 1826. This catalogue, which became known as "The Brisbane Catalogue", was printed in London in 1835.

Governor Brisbane returned to Europe at the end of 1825. However, as previously stated, Dunlop stayed in NSW and continued working from his home at Parramatta, '*6" of a degree south, and about 1.78" of time east of the Brisbane Observatory*' (Service 1890, p. 146). He particularly observed nebulae and groups of stars. Dunlop eventually left NSW in 1827 and rejoined Sir Thomas in Scotland.

Figure 1: James Dunlop, 1826. ©Mitchell Library, State Library of NSW.

Dunlop presented a paper, on nebulae and star clusters, to the Astronomical Society of London in December 1827. The Society published his observations in 1828 and both he and Brisbane received the societies gold medals of the year, for their astronomical work at Parramatta Observatory. In his manuscript Dunlop stated '*I trust this catalogue of the nebulae* [sic] *will be found an acceptable addition to that knowledge which the Brisbane observatory has been the means of putting the world in possession of, respecting that important and hitherto but little known portion of the heavens*' (1828, p. 114).

Dunlop remained in Scotland working at Brisbane's newly completed, 1826, observatory at Makerstoun. During this period, 1827–1831, Sir Thomas and Dunlop began geomagnetic observations throughout Scotland. Brisbane, like many astronomers of his time, had a keen interest in understanding the distribution of magnetic intensity. Sir Thomas states in Dunlop (1834b, p. 1) '*the regret I feel that this important branch of science should have been so much neglected in Great Britain*'.

Cawood quotes Harcourt's 1839 address to the British Association regarding the investigation of the magnetic field's importance not just as a navigation tool but as '... *a completion of what Newton began – a revelation of new cosmical* [sic] *laws*' (Cawood 1979, p. 493). Tasker (1860) describes Sir Thomas' continuous pursuit in this field of science and his later construction of his Magnetic and Meteorological Observatory at Makerstoun in 1841.

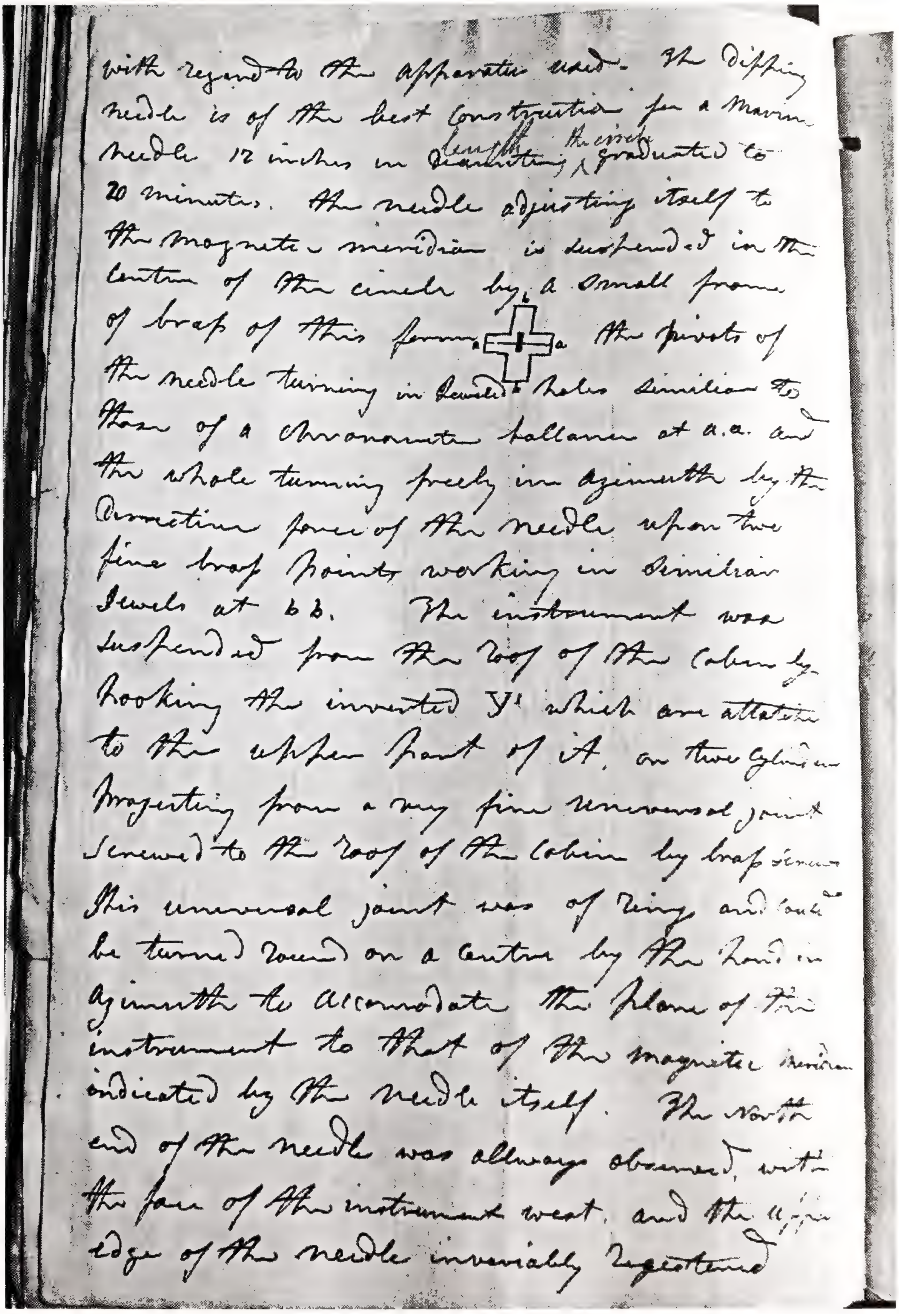

with regard to the apparatus used. The dipping
needle is of the best construction for a marine
needle 12 inches in length the circle graduated to
20 minutes. the needle adjusting itself to
the magnetic meridian is suspended in the
centre of the circle by a small frame
of brass of this form a the pivots of
the needle turning in jewelled holes similar to
those of a chronometer ballance at a.a. and
the whole turning freely in azimuth by the
directive force of the needle upon two
fine brass points working in similar
Jewels at b.b. The instrument was
suspended from the roof of the Cabin by
hooking the inverted Y's which are attached
to the upper part of it, on two Cylinders
projecting from a very fine universal joint
Screwed to the roof of the Cabin by brass screws
this universal joint was of ring and could
be turned round on a centre by the hand in
azimuth to accomodate the plane of the
instrument to that of the magnetic meridian
indicated by the needle itself. The north
end of the needle was allways observed, with
the face of the instrument west, and the upper
edge of the needle invariably registered

Figure 2. Page 2 from Dunlop's unpublished manuscript (Dunlop 1834a). Photographed by Ms Gail Gibson, London.

MEASURING MAGNETIC FIELDS

'In the 19th century the three recorded "elements" of the earth's magnetic field were the intensity, the declination, and the inclination. The intensity, which was measured by counting the number of oscillations of a magnetized needle in a fixed interval, could be determined either parallel or perpendicular to the direction of the field at a given location. The declination, which was often known as "variation" in Britain, was the difference between true north and magnetic north at a particular point, and the inclination, or "dip" was the angle between the vertical direction of the field and the horizon measured in the plane of magnetic north.' (Cawood 1979, p. 495)

Robert Norman a London instrument-maker first published results of magnetic needle experiments in 1581. McConnell states '*... his carefully-balanced compass needles, when subsequently magnetised, always took up a position in which the north-seeking point hung downwards*' (1980, p. 12). Further experiments, with a magnetised needle held in a horizontal position, ascertained the swing and angle the needle would reach in its magnetic attraction. The angle is read from a graduated circle attached to the apparatus.

In 1830, before the Royal Society of Edinburgh Sir Thomas Makdougall Brisbane presented Dunlop's paper '*An Account of Observations made in Scotland on the Distribution of the Magnetic Intensity*' (Dunlop 1834b). Sir Thomas introduced Dunlop's presentation and subsequent paper, '*Mr Dunlop has so fully and clearly detailed his mode of proceeding with these observations, ... that, in point of number, extent of country, combined with precaution, accuracy, and consistency, I consider they are unrivalled in this or any other country*' (Dunlop 1834b, p. 1).

Following his years with Brisbane at Makerstoun, Dunlop's interest and ability to conduct magnetic research is evident. Upon the announcement that Dunlop is appointed Superintendent of Parramatta Observatory, the opportunity to conduct magnetic observations during his voyage to New South Wales is timely. The Admiralty Hydrographer, Captain Francis Beaufort R.N. extracts a pledge from Dunlop to carry out this arduous task.

The first observations commenced on the 4th June 1831 from the 'Mary' and the final series noted, from this ship, occurred that year on the 17th October. In total, Dunlop recorded for 332 days covering the thousands of miles from Woolwich to Hobart Town. This, across the seas, study continued whilst travelling aboard the Brigg 'Helen' from October 31st 1831 until his arrival in Sydney Town on November 6th.

Dunlop describes the preparation of his cabin for the experiments (Figure 2) and includes a sketch of the apparatus. He goes on to give details, on page 11, of both his mechanical skills and innovative thinking. '*In the year 1828 I made a number of needles in the expectation of obtaining from the whole two or three in which the magnetism had become stationary – but was disappointed. It occurred to me that I had an old C* [indecipherable word] *by Ramsden with an excellent needle about 2 1/2 inches in length. I took out the needle and by means of shellac varnish cemented a silver loop on the top.*' (Dunlop 1834a, p. 11). As previously revealed, Dunlop not only kept his promise to Captain Beaufort but he supplemented the magnetic research he recorded, during his voyage to NSW, by further land/sea observations until January 16th 1833. Dunlop reduced the data he gathered over these years in a similar manner to those readings taken during his travels through Scotland. '*With regard to ... these observations – the corrections applyed* [sic] *for the reduction to 60° of temperature ... and those for Arc of vibration depend on the cosine of the difference of the mean of the arcs. Commencing with an arc of 20 and ending with an arc of 5 degrees on land being the standard. But at sea there will be some uncertainty respecting the mean of the arc of vibration because the motion of the ship particularly in rough weather will make the arc irregular during a series. Though in moderate weather and the ship going free the observations are in general equal to any I could have made on shore.*' (Dunlop 1834a, p. 6)

In the nineteenth century, astronomer Sir Edward Sabine was the driving force in a British push to organise and establish a worldwide

chain of magnetic observatories. Observations for this international venture commenced in 1840. Apart from the official publications generated by the various institutions Sabine published compilation reports of magnetic surveys in the Philosophical Transactions of the Royal Society.

After finding the unpublished manuscript in the annals of the Royal Society, Sabine utilised Dunlop's observations taken during his 1831 voyage to NSW. In the Philosophical Transactions of the Royal Society of London Sabine published 'Contributions to Terrestrial Magnetism' in 1840, with acknowledgment of Dunlop's labour. Between 1840 and 1877, Sabine published fifteen volumes of this series of observations. Throughout the successive papers, he continued to make use of Dunlop's unpublished manuscript. '*Mr. DUNLOP'S observations ... furnish us with a series of dip and intensity results obtained at sea between the meridian of the Cape of Good Hope and New South Wales, and between the parallels of -35° and -41°; a part of the globe from whence no* ***recent*** *data at least have been obtained for the lines of dip, and where materials for the lines of intensity were previously wholly wanting.*' (Sabine 1840, p. 142)

JAMES DUNLOP RETURNS TO PARRAMATTA

Dunlop's return to Parramatta in 1831 was to take up the position of Superintendent of Parramatta Observatory. He discovered a comet in 1833 and another in 1834. The scientific community again honoured Dunlop, this time for these discoveries. He received the Lalande medal from the Académie des Sciences. '*The medal created by M. de Lalande to be given every year to the person who, in France or elsewhere (members of the Institute excepted) has done the most interesting observation or the communication most useful to the progress of astronomy, has been given in 1835 to Mr Dunlop, director of the Observatory of New Holland*'. (Académie des Sciences 1835, p. 521. translation by Babron, May 2003).

In 1834, John Herschel travelled to South Africa and commenced a four-year examination of the skies of the southern hemisphere. His observations included viewing the return, in 1836, of Halley's Comet, and evaluating the brightness of stars. Whilst on this South African expedition Herschel raised doubts regarding the authenticity of observations taken at Parramatta. The number of observations with '*so small a telescope*' (Cozens & White 2001, p. 114) seemed implausible. Herschel found '*only 211 of Dunlop's objects in spite of using a substantially larger telescope ... he* [Herschel] *remarked that Dunlop saw them from "subjective reasons"*'. (Cozens & White 2001, p. 114).

Due mainly to John Herschel's disparagement, of the work performed at Parramatta the observations fell into disrepute. Herschel's own objectivity, perhaps professional jealousy, regarding his comments is questioned by Agnes Mary Clark and cited by Cozens & White as Herschel felt ... 'the cream of the Southern Hemisphere had already been skimmed by Dunlop' (2001, p. 114).

Dunlop continued to observe and note both meteorological and astronomical data for many years. Although his last recorded observations were in 1839, James Dunlop remained at Parramatta and the Observatory until 1847 when illness forced him to resign.

The Sydney Morning Herald retirement notice reads '*Mr Dunlop, the Astronomer Royal of the Colony, has resigned his appointment. During the many years Mr. D. has held this most distinguished appointment, he has made it a fixed rule of his life to distribute in acts of charity the salary he received from the Admiralty, with whom the appointment is vested*' (1847).

The article continues by mentioning some of Dunlop's prestigious awards and the preparation for a parting function. Unfortunately, due to the sudden death of the Governor's wife, no farewell event occurred. James Dunlop retired to his home at Brisbane Waters where he died the following year. His published death notice is in The Sydney Morning Herald, for September 1848 but the date of death is recorded as 22nd September whilst his gravestone states 23rd September.

A TANGIBLE RESULT

All the equipment from Parramatta Observatory was stored prior to the demolition of the building in 1847–48. Holland has recently (2008) unearthed more details of these particular circumstances. Examination of Brisbane's papers, when he furnished his first observatory at Brisbane Glen, Scotland, finds an account (1809, 1810) for the acquisition of some astronomical instruments. They show no record of Brisbane purchasing a dipping needle/compass at this time. Further investigation may lead to its purchase occurring whilst he was stationed in Paris between 1815 and 1818. Although online records do not detail its provenance there is a Gambey of Paris dipping needle in the collection of the Powerhouse Museum in Sydney with an observatory index code. This instrument is shown in Figures 3 & 4. Evidence suggests it is part of the original observatory equipment bought to NSW by Governor Sir Thomas Brisbane. Records include the magnetic observations taken by Brisbane and Rümker during the voyage to NSW and published in 1830 by Rümker. This paper contains a report of a magnetic reading (p. 2) upon their arrival in November 1821 using a Gambey of Paris dipping compass. When Brisbane left the colony in 1825, the instrument was amongst the equipment purchased, with the observatory, by the Colonial Government.

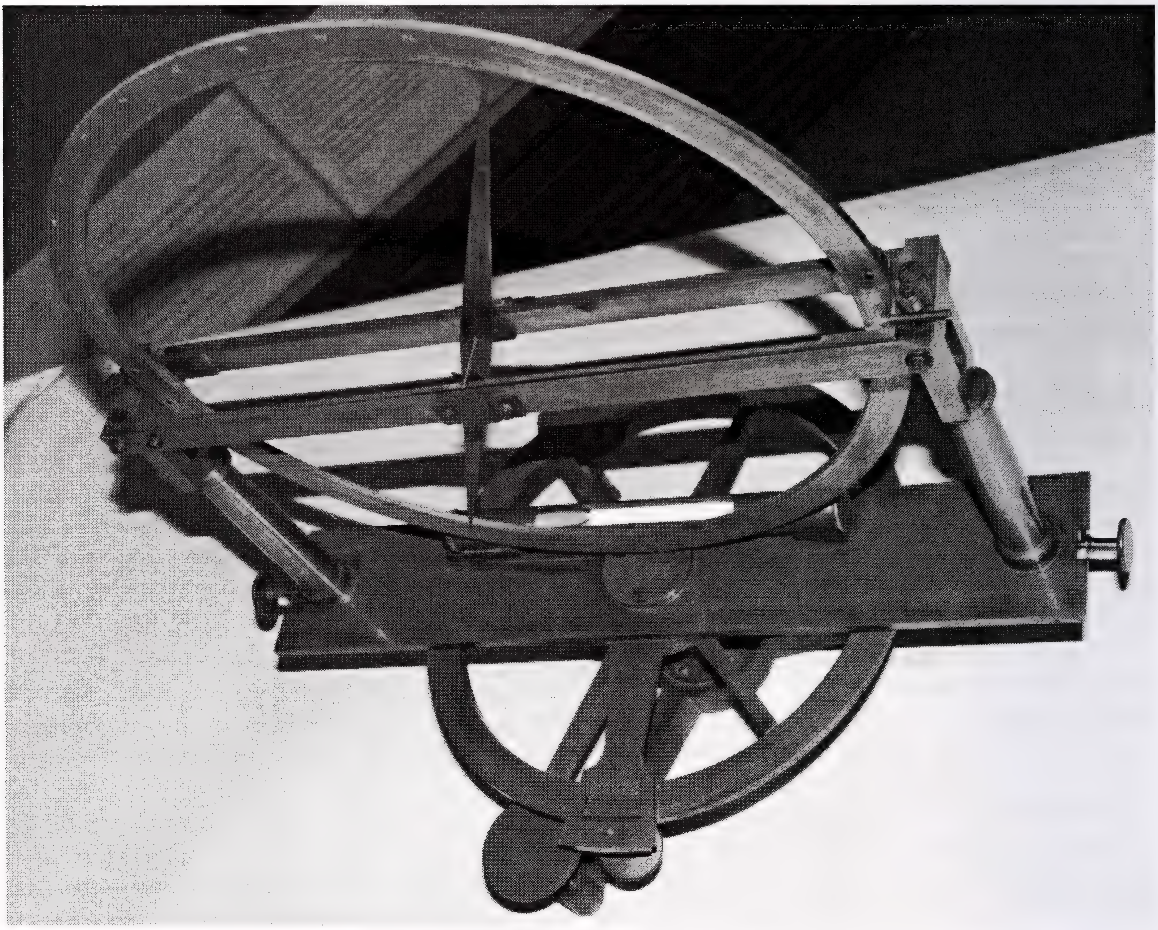
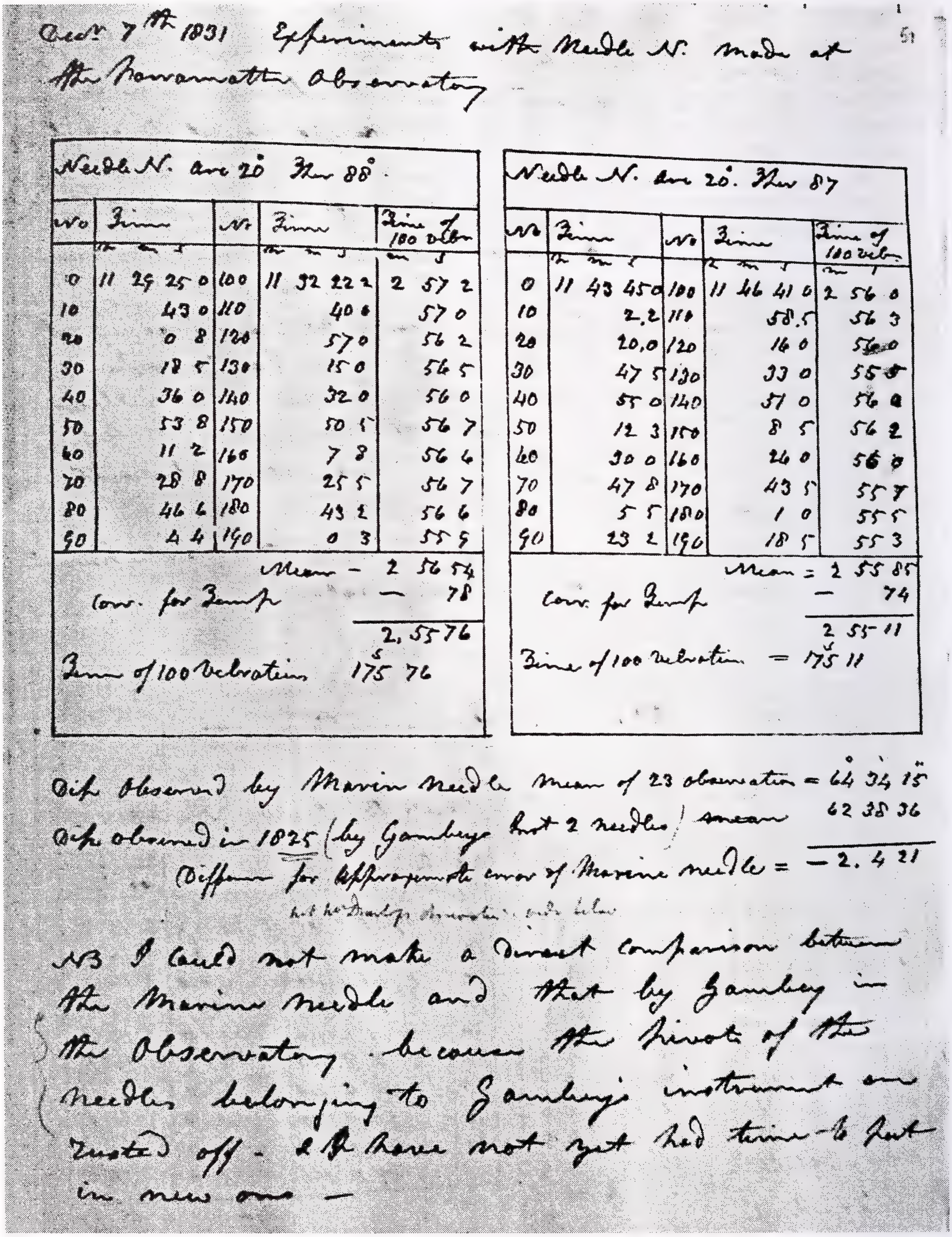


Figure 3. Gambey of Paris dipping needle/compass from Sydney Observatory.
Photograph by author, courtesy Dr Nick Lomb, Curator of Astronomy, Powerhouse Museum.

Dunlop's unpublished manuscript again discusses the Gambey of Paris dipping needle. He notes observations, using this instrument, for 1825 but he is unable to duplicate the experiment in 1832 because of the rusty condition of the '*pivots of the needles*' (Dunlop 1834a, p. 126, see Figure 5). Due to its historical significance, further research to confirm the provenance of this instrument is warranted.

As previously mentioned, Brisbane and Rümker also conducted magnetic observations during voyages to and from NSW, but although their results were published, they were not as wide-ranging as Dunlop's 1831 series. (Figure 6 aptly illustrates the extent of Dunlop's magnetic observations.) The worth of James Dunlop's comprehensive magnetic observational work was not overtly credited during his lifetime and this oversight should finally be recognised.

Figure 4. Detail of the Gambey of Paris dipping needle/compass from Sydney Observatory. Photograph by Dr Nick Lomb, Curator of Astronomy, Powerhouse Museum.



Octr 7th 1831 Experiments with Needle N. made at the Parramatta Observatory

Needle N. arc 20° Ther 88°				
No	Time	No	Time	Time of 100 vibr
	h m s		h m s	m s
0	11 29 25 0	100	11 32 22 2	2 57 2
10	43 0	110	40 0	57 0
20	0 8	120	57 0	56 2
30	18 5	130	15 0	56 5
40	36 0	140	32 0	56 0
50	53 8	150	50 5	56 7
60	11 2	160	7 8	56 6
70	28 8	170	25 5	56 7
80	46 6	180	43 2	56 6
90	4 4	190	0 3	55 9

Mean – 2 56 54
Corr. for Temp — 78
2, 55 76
Time of 100 vibrations 175 76

Needle N. arc 20°. Ther 87				
No	Time	No	Time	Time of 100 vib
	h m s		h m s	m s
0	11 43 45 0	100	11 46 41 0	2 56 0
10	2,2	110	58,5	56 3
20	20,0	120	16 0	56 0
30	47 5	130	33 0	55 5
40	55 0	140	51 0	56 0
50	12 3	150	8 5	56 2
60	30 0	160	26 0	56 0
70	47 8	170	43 5	55 7
80	5 5	180	1 0	55 5
90	23 2	190	18 5	55 3

Mean = 2 55 85
Corr. for Temp — 74
2 55 11
Time of 100 vibration = 175 11

Dip observed by Marine needle mean of 23 observation = 64 34 15
Dip observed in 1825 (by Gambey but 2 needles) mean 62 38 36
Difference for approximate error of Marine needle = – 2. 4 21

NB I could not make a direct comparison between the Marine needle and that by Gambey in the Observatory because the pivots of the needles belonging to Gambey's instrument are rusted off - & I have not yet had time to put in new ones —

Figure 5. Page 126 from Dunlop's unpublished manuscript (Dunlop 1834a). Photographed by Ms Gail Gibson, London. ©Royal Society, London

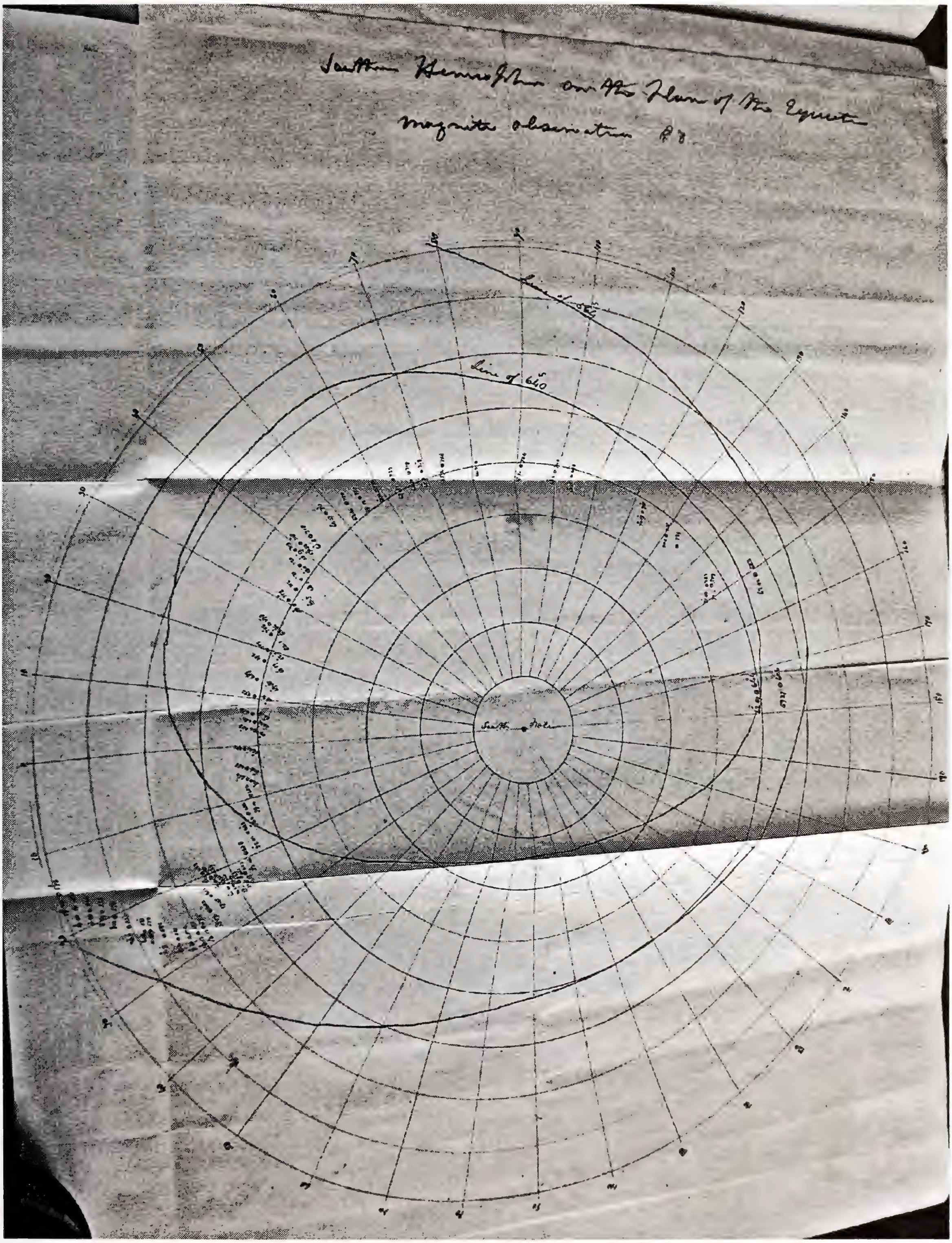


Figure 6. Page 148 from Dunlop's unpublished manuscript (Dunlop 1834a).
Photographed by Ms Gail Gibson, London. ©Royal Society, London

IN CONCLUSION

An almost forgotten figure in Australian colonial history James Dunlop travelled across the world and participated in the establishment of Parramatta Observatory and the cataloguing of the southern sky. The initial accolades he received from the European scientific community, for his contributions to astronomy, turned to condemnation. On his second voyage to NSW, Dunlop conducted difficult research and then reduced the accumulated results into a manuscript. This document was never printed (Figure 7 records the Royal Society's decision) and his carefully prepared data only became accessible under the authorship of another.

It is just over 160 years (September 23rd 1848) since James Dunlop died in his home at Brisbane Waters and his work and life have almost disappeared from our historical records. This International Year of Astronomy is an appropriate time to recognise James Dunlop as part of Australia's scientific heritage and to reclaim some of his reputation.

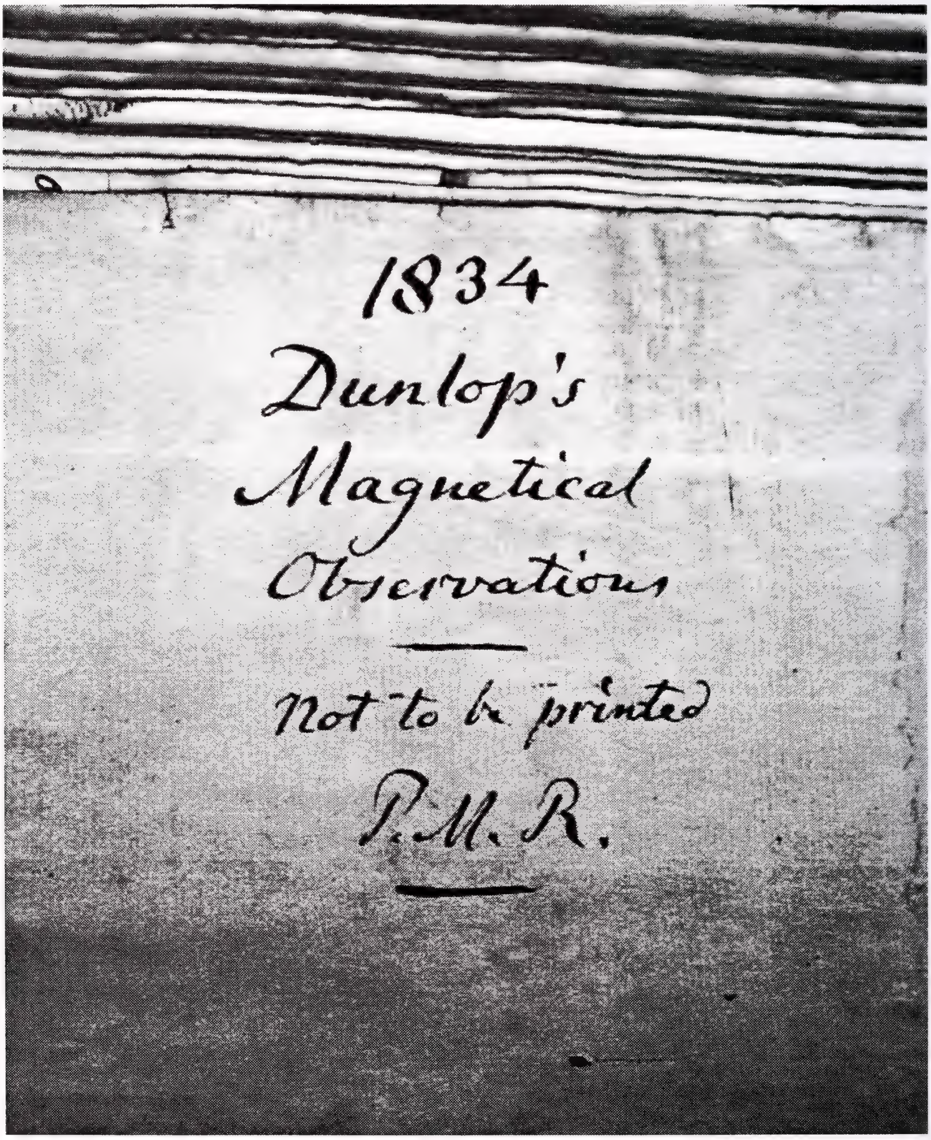


Figure 7. Page 147 from Dunlop's unpublished manuscript (Dunlop 1834a). Photographed by Ms Gail Gibson, London. ©Royal Society, London

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Tectonostratigraphic Evolution of the Blantyre Sub-basin and Adjacent Regions, New South Wales, Based on Integration of Seismic, Gravity and Well Data

MOHAMED KHALIFA

Abstract: This paper presents the principal tectonostratigraphic features within the Blantyre Sub-basin, a central part of the regional Darling Basin, that results from deformation of the latest Silurian to Devonian sequence. This case study shows that by integrating well data, seismic data and gravity data, conceptual geologic models in the Blantyre Sub-basin and surrounding area can be constructed. Integration of the gravity contour map with two-way time structure contour maps suggest that five major structural features can be identified: (a) the Mount Emu High that is interpreted as an anticlinal fold with an associated thrust fault, (b) the Wilcannia High, interpreted as an uplift, clearly identified on the northern margin of the Blantyre Sub-basin, (c) the Snake Flat High, interpreted as an asymmetric anticlinal fold with a number of high-angle reverse faults, (d) a structural low occurring in the central part of the Blantyre Sub-basin, interpreted as an elongate synclinal fold that covers an area of approximately 400 square kilometres, and (e) another small structural low, interpreted to be a synclinal fold. Structure and isochore maps reveal that faults profile the primary control on subsidence patterns. Understanding these structural features should help to decrease the risks for hydrocarbon exploration by applying better defined and up-to-date concepts throughout the Blantyre Sub-basin.

Keywords: Blantyre Sub-basin, latest Silurian-Devonian sequence, basin analysis, seismic data interpretation, gravity data, structure and isochore map, tectonostratigraphic model.

INTRODUCTION

The Darling Basin is potentially one of the most important areas in New South Wales for petroleum exploration, with over 8000 metres of sediment that range in age from Precambrian to Late Palaeozoic. The Darling Basin consists primarily of four sub-basins, the Pondie Range, Blantyre, Neckarboo and Nelyambo Sub-basins (Figure 1). It also includes three major troughs, the Bancannia, Menindee and Poopelloe Lake Troughs (Figure 1), (Byrnes 1985; Evans 1977; Encom Technology Pty Ltd 1994; Glen et al. 1996; Bembrick 1997a, b; Pearson 2003; Neef 2005; Khalifa 2005; Khalifa and Ward 2009). Data from geologic mapping, seismic profiles, gravity data, and wells are used here to describe the tectonostratigraphic history of the Blantyre Sub-basin, focusing on the latest Silurian-Devonian sequence.

Recently, Neef and Bottrill (1991), Neef (2005), Encom Technology Pty Ltd (1994), Bembrick (1997a,b), Alder et al. (1998), Willcox et al. (2003), Pearson (2003), Cooney and Mantaring (2007) provided further data that document the Winduck, Snake Cave and Ravendale Intervals as the principal latest Silurian-Devonian sequences in the Darling Basin. However, tectonostratigraphic units proposed in this study fundamentally differ from the physical stratigraphy and depositional models suggested by Bembrick (1997a, b), Alder et al. (1998).

The main focus of the present study is the Blantyre Sub-basin, which covers an area of approximately 14,000 square kilometres in the central part of the Darling Basin shown on Figure 1. The stratigraphy and structural geology of the Blantyre Sub-basin is based on an interpretation of seismic profiles, well logs and gravimetric anomalies. The Blantyre Sub-basin is bounded by the Wilcannia High in the north and northeast, by the Lake Wintlow High in the west, by the Neckarboo Sub-basin in the southeast, and the Neckarboo High in the south (Figure 1).

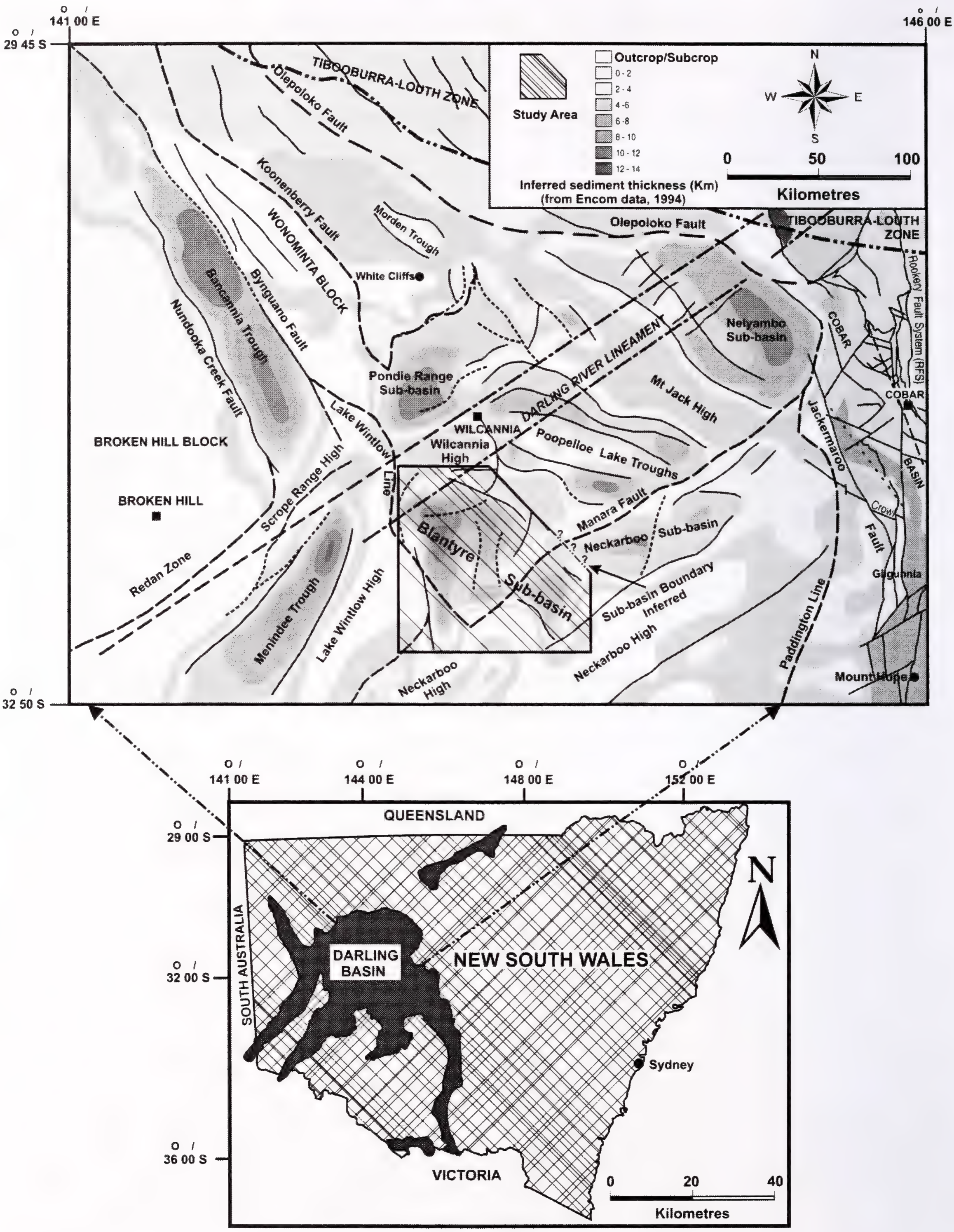

Figure 1. Regional map of Darling Basin showing structural features and important sub-basins, troughs and highs with location map of the Blantyre Sub-basin (Modified after Glen et al. 1996).

According to Encom Technology Pty Ltd (1994), the Blantyre Sub-basin has a basement depth estimated from seismic data near Blantyre-1 well that indicates a sediment thickness of 11–12 kilometers. The amplitude of the Bouguer gravity anomaly from the basement on the western flank of the Blantyre Sub-basin to the basement in the centre of the area is 57 mgal. The gravity data, obtained from the Australian Geological Survey Organization base, were acquired from ground gravity methods; a very tight grid has been recorded in the vicinity of the Snake Flat-1 well in the Blantyre Sub-basin with an average station spacing of approximately 700 metres (NSW Department of Mineral Resources, 1993).

The aim of this paper is to discuss the geometry and structure of the three main conceptual tectonostratigraphic packages of latest Silurian-Devonian sequences in the Blantyre Sub-basin using reflection seismic profiles, well data and the Bouguer gravity map. Recent advances in our understanding of three-dimensional geological models have also been compared to information from detailed gravity surveys in the area, and interpreted in the light of the regional tectonic setting to develop a better understanding of the relationship between the structural development and the depositional processes in the latest Silurian-Devonian sequences (e.g. Winduck, Snake Cave and Ravendale Intervals). In addition, many of the key well penetrations of the latest Silurian-Devonian sequence were tied to regional seismic profiles (e.g. Blantyre-1, Mount Emu-1, Booligal Creek-1, Booligal Creek-2, Snake Flat-1 and Kewell East-1) (Table 1). Additional regional seismic sections were also constructed to assist the analysis process, further clarifying the relation between the stratigraphy, sub-basin geometry, history and the regional structural style (e.g. major faults and folds).

STRATIGRAPHIC SUMMARY

A summary of the latest Silurian to Early Permian stratigraphic succession of the Darling Basin and surrounding region is given below.

Latest Silurian and Devonian Sequence

The latest Silurian to Devonian succession in the Darling Basin is summarized in Table 2. Using terminology for the central part of the basin as described by Rose (1968) and Packham (1969), the succession in these areas is subdivided on the basis of regional unconformities into three major intervals as follows: (1) Latest Silurian to Early Devonian (Pragian) Winduck Group and equivalents, (2) Early Devonian (Emsian) to Middle Devonian (Eifelian) Snake Cave Sandstone and equivalents, and (3) Middle Devonian (Givetian) to Late Devonian (Famenian) Ravendale Formation and equivalents. The uppermost two units in this sequence, the Snake Cave Sandstone and the Ravendale Formation, are generally correlated with the Mulga Downs Group, a unit originally defined on the basis of outcropping strata in the area west of Cobar (Rayner 1962).

Bembrick (1997a, b) and Alder et al. (1998) used three seismic horizons, originally described by Evans (1977), to divide the stratigraphic sequence of the Darling Basin into three informally named 'Intervals', as an initial reference framework to describe the strata within this poorly exposed and sparsely drilled area. These intervals (Table 2) are broadly equivalent to the main lithostratigraphic units identified from outcrop studies, but are defined on the basis of seismic marker horizons rather than lithologic criteria. Bembrick (1997a, b) and Alder et al. (1998) related the unconformities associated with the seismic markers to significant tectonic events in the geological history of the region. Horizon A was considered to mark the Bowning event, an angular unconformity of latest Silurian age; Horizon B was taken as representing the Bindian event, a regional unconformity of late Early Devonian age; and Horizon C was considered to mark the Tabberabberan event, a regional unconformity of late middle Devonian age (Table 2).

Well name	KB. (metres)	TD. (metres)	Informal stratigraphy	Unit top (metres)	Thickness (metres)	References
Blantyre-1	77	2289	Lower Permian	235.61	66.14	Bembrick 1997b
			Upper Carboniferous?	301.75	103.55	
			Ravendale Interval	405.3	1784.7	
			Snake Cave Interval	2190	99	
Mount Emu-1	80.2	1450.5	Snake Cave Interval	368.9	243.1	Khalifa 2005 and Khalifa & Ward 2009
			Winduck Interval	612	838.5	
Booligal Creek-1	80.2	409.5	Winduck Interval	260	149.5	Khalifa 2005 and Khalifa & Ward 2009
Booligal Creek-2	80.2	761.4	Winduck Interval	238	523.4	
Kewell East-1	79.9	1224	Snake Cave Interval	88	290	Clark et al. 2001
			Winduck Interval	378	846	
Snake Flat-1	4	353.5	No Mulga Downs Group and Winduck Interval	–	–	Maple Oil N.L. 1994

Table 1. Generalized informal stratigraphy, top and thickness of the lithostratigraphic units drilled within Blantyre Sub-basin.

Period	Epoch	Age	Generalised Lithostratigraphic Units *West* ---		*Central*			--- *East*
LATE CARBONIFEROUS/ EARLY PERMIAN			--- Unnamed unit --- ***Kaninmblan Event~Regional Unconformity ~Seismic Marker Reflector (Horizon-D)***					
DEVONIAN	LATE	FAMENNIAN FAASNIAN	--- Ravendale Interval --- --- Bembrick (1997a,b) ---	Nundooka Sandstone (1070 m) Ward *et al* (1969)	Ravendale Formation (800 m) Rose (1968) Packham (1969)	Unit-C (375 m) Unit-B (120 m) Uint-A (600 m) Carroll (1982)	Crowl Creek Formation (2000 m) Bundycoola Formation (300 m) Glen (1982a)	--- Mulga Downs Group --- --- Mulholland (1940) and Rayner (1962) ---
	MIDDLE	GIVETIAN	***Tabberabberan Event~Regional Unconformity ~Seismic Marker Reflector (Horizon-C)***					
		EIFELIAN	--- Snake Cave Interval --- --- Bembrick (1997a,b) ---	Coco Range Beds (760 m) Ward *et al* (1969)	Snake Cave Sandstone Rose (1968) (120 m) Packham (1969) (2285 m)	Unit (5, 6 & 7) (100-900 m) Unit (1, 2, 3 & 4) (250-550 m) Carroll (1982)	Bulgoo Formation (2600 m) Merrimerriwa Formation (200-300 m) Meadow Tank Formation Glen (1982a)	
	EARLY	EMSIAN	***Bindian Event~Regional Unconformity ~Seismic Marker Reflector (Horizon-B)***					
		EMSIAN PRAGIAN LOCHKOVIAN	Mt Daubeny Formation Neef *et al* (1989) and Neef and Bottrill (1991)	Winduck Group	--- Glen (1979, 1982b) --- Gundaroo Sandstone (90 m) Sawmill Tank Siltstone (500 m) Buckambool Sandstone (1000 m)	Unit-A1 (40 m) Unit-A2 (50 m)	Amphitheatre Group Andrews (1913) and Rayner (1962)	--- Winduck Interval --- --- Bembrick (1997a,b) ---
LATEST		SILURIAN	***Bowning Event~Angular Unconformity ~Seismic Marker Reflector (Horizon-A)***					

Table 2. Lithostratigraphic units nomenclature correlation of the latest Silurian to Devonian sequence in the Darling Basin. Seismic marker unconformities (A, B, C, D) from Evans (1977) are correlated with the three informally named 'Intervals' described by Bembrick (1997a, b).

The Mulga Downs Group, which is the main focal point of this study, is one of the major thick clastic successions of late Early Devonian to Late Devonian age in western New South Wales. This Devonian sequence, originally referred to as the Mulga Downs Stage (Mulholland 1940) but re-defined as the Mulga Downs Group by Rayner (1962, cited in Conolly et al. 1969), has been subdivided into several formations and mapped by authors such as Conolly (1962), Rose (1968), Ward et al. (1969) and Glen (1979, 1982a, 1986). Bembrick (1997a, b) also suggested that the Mulga Downs Group required re-definition based, among other as-

pects, on regional mapping by Glen (1986), and avoided using the term in his discussion. Such a framework, based on mapping and correlation of seismically defined units, also provide a useful stratigraphic framework for the present study.

Winduck Interval and Equivalents

The Winduck Interval is widespread throughout the Darling Basin, both in outcrop and in the subsurface. These strata are represented by the Mt Daubeny Formation in the western part of the basin (Neef et al. 1989), the Winduck Group in the central to eastern part (Glen 1982a, b; Scheibner 1987), and the Amphitheatre Group in the eastern part of the basin (Andrews 1913; Rayner 1962) (Table 2).

The depositional environment of the Winduck Interval shows an overall regressive nature from west to east across the Darling Basin. It generally ranges from alluvial/fluvial in the Mt Daubeny Formation through fluvial to deltaic/shoreline in Winduck Group (Glen 1982a,b; Neef 2005; Neef et al. 1989; Neef and Bottill 1991) and deeper marine within Amphitheatre Group in the east (Glen 1982b, 1986).

Snake Cave Interval and Equivalents

The lower part of the Mulga Downs Group was formally proposed as the Snake Cave Interval by Bembrick (1997a, b). This interval is equivalent to the Snake Cave Sandstone in the Mt Wright area (Rose 1968), and in the eastern part of the Bancannia Trough (Packham 1969; Carroll 1982). It also includes the Coco Range Beds (now Coco Range Sandstone, Neef et al. 1995) on the western flank of the Bancannia Trough (Ward et al. 1969). In the east the interval has been subdivided into a lower part, the Meadows Tank Formation, a middle part, the Merrimerriwa Formation, and an upper part, the Bulgoo Formation, in the Buckambool area (Glen 1979, 1982a) (Table 2).

The depositional sequence of the Snake Cave Interval was initiated by braided and alluvial fan input from the west within the Valley Tank Member in the western part of the basin and from the south-west for the Meadows Tank Formation in the eastern and central parts of the basin (Glen 1979, 1982a). At this time, the central parts of the Darling Basin were relatively free of coarse siliciclastic sediments and minor carbonates were developed locally (Rose 1968; Conolly et al. 1969; Carroll 1982; Neef and Larsen 2003).

Ravendale Interval and Equivalents

The upper part of the Mulga Downs Group is equivalent to the subsurface Ravendale Interval proposed by Bembrick (1997a, b). The interval is equivalent to the Ravendale Formation named by Rose (1968). Conolly et al. (1969) has described the Ravendale Formation near the Bancannia Trough. The unit is synonymous with Units A, B and C mapped by Carroll (1982) on the eastern side of the Bancannia Trough. The Ravendale Formation is equivalent to the Nundooka Sandstone, mapped on the western flank of the Bancannia Trough by Ward et al. (1969). The lower part is also equivalent to the Bundycoola Formation and the upper part to the Crowl Creek Formation in the Buckambool area, west of Cobar (Glen 1982a), as shown in Table 2.

In general the Ravendale Interval is initiated by an influx of coarse siliciclastic sediments in both the western and eastern parts of the basin (Ward et al. 1969; Conolly et al. 1969; Neef et al. 1995, 1996). Few coarse clastic types of sediment reached the central regions of the basin (Neef et al., 1995; Bembrick 1997a, b). The depositional environment of the Ravendale Interval is dominantly fluvial, but closes with a Famennian marine episode encountered in the structural troughs where the thicker Late Devonian section is preserved (Neef and Larsen 2003; Bembrick 1997b).

Late Carboniferous to Early Permian Sequence

In the southern part of the Darling Basin, rocks of Late Carboniferous to Early Permian age have been recognized in several different studies (Byrnes 1985; Bembrick 1997b). Horizon D was considered to mark the Kanimblan event, a regional unconformity of Late Carboniferous age (Evans 1977) (Table 2). Areas in which

such beds have been noted include the Blantyre Sub-basin. The lithology of these strata is dominated by interbedded siltstones and sandstones, which are variably micaceous and carbonaceous. Thick sections of Late Carboniferous to Early Permian strata have also been encountered in wells drilled in the Wentworth and Tararra Troughs (Evans 1977). Evans (1969) and Veevers and Evans (1975) considered from microfloras in the sequence that the rocks are mainly Late Carboniferous in age. However, rocks of Early Cretaceous age are known in the subsurface of the northern Bancannia Trough, and have also been encountered in wells to the south near Wentworth and Mildura (Evans and Hawkins 1967).

STRUCTURAL FRAMEWORK

Integration of lineament data within the Darling Basin shows that the boundaries are marked by a complex of major structural features as shown in Figure 1. The basin can be divided into six structural zones and one sub-zone, each representing distinct fault-bounded blocks (Scheibner 1993), and perhaps into several less distinct geologic terranes (Scheibner 1972, 1976; Evans, 1977; Glen et al. 1996; Glen and Walshe 1999; Pearson 2003; Neef 2005; Cooney and Mantaring 2007).

The basin appears to be bounded in the north and east by the Tibooburra-Louth Zone (Scheibner 1989; Scheibner and Basden 1996, 1998), the Olepoloko Fault (Stevens and Crawford 1992) and the Paddington Line (Glen et al. 1996) (Figure 1). The western margin, against the Broken Hill Block, is represented by the NW-trending Nundooka Fault in the Bancannia Zone, and by the southwest trending southern margin of the Redan Zone (Scheibner 1993) (Figure 1).

Significant faults and other features within the basin include the NW-SE trending Koonenberry Fault (Rose and Brunker 1969; Leitch et al. 1987; Neef and Larsen 2003; Neef 2005), the prominent ENE-trending Darling River Lineament (Hills 1956), and the Bynguano Fault (Buckley 2001) on the eastern side of the Bancannia Trough. The Lake Wintlow Line separates the Bancannia Trough and the Pondie Range Sub-basin in the north and the Menindee Trough and Blantyre Sub-basin in the southwestern part of the basin.

The structural features of the Blantyre Sub-basin were described by Glen et al. (1996). The Manara Fault changes from NW trending in the SE part of the sub-basin to NW-trending near the Nelyambo Sub-basin. Uplift of the Wilcannia High, as defined by Evans (1977), appears to indicate the development of another major structural feature within the sub-basin. The Lake Wintlow Line provides a well-defined feature separating the Blantyre Sub-basin from the Menindee Sub-basin (Encom Technology Pty Ltd 1994; Glen et al. 1996; Alder et al. 1998). The Neckarboo High, along the southeastern margin of the Neckarboo Sub-basin and the southern margin of the Blantyre Sub-basin, is a narrow, elongate feature, which is approximately 60 kilometres long (Alder et al. 1998; Pearson 2003) (Figure 1).

DATA COLLECTION AND METHODOLOGY

Database

The database used for this study consists of data from five exploratory petroleum wells and approximately 800 km of conventional two-dimensional seismic reflection profiles drawn from four different data sets (Figure 2). The Appendices summarize seismic data acquisition and processing parameters. This seismic data set was then integrated with Bouguer gravity data in order to identify and map the major structural features within the Blantyre Sub-basin (Figure 2).

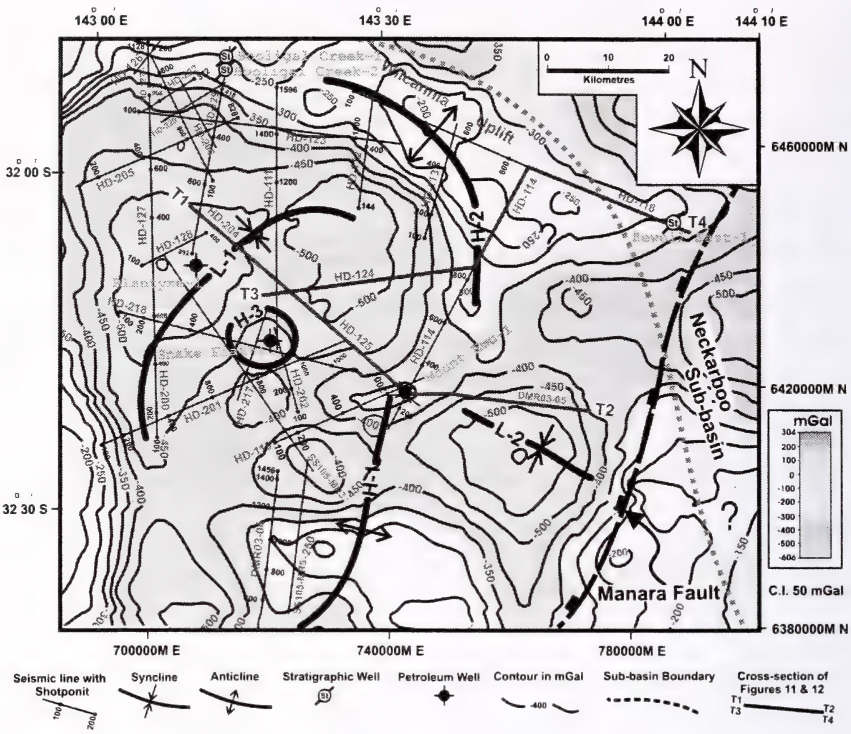

Figure 2. Map showing gravity anomaly with distribution of two-dimensional (2-D) seismic profiles. Location of wells drilled within the Blantyre Sub-basin (modified after NSW Department of Mineral Resources, 2003). Also shown are hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as determined in Figures 3, 4 and 5.

The two-dimensional seismic reflection data sets were integrated and re-interpreted using a range of computer-based techniques, particularly the Kingdom® processing suite. Information from the seismic and well studies was integrated using CorelDraw® 11 (e.g. for preparation of seismic cross-sections) and Surfer 8 for preparation of contour maps and three-dimensional geologic evaluations.

The two-way travel time at selected shot points, about 100 metres apart on each of the seismic sections, was estimated for each reflector. The resulting data (the eastings and northings of each shot point and the two-way travel time to the reflector at that shot point) were input to the Surfer 8 graphic modelling package, to develop contour maps of the individual horizons. Areas where the relevant horizons were not present, especially in modelling the base of the Ravendale Interval, were excluded from the modelling process.

Interpretation Methods

The data were interpreted in four steps. It should be noted, however, that tectonostratigraphic modelling is very much an iterative process between the different steps, and hence the succession of processes was repeated several times in developing the final output of the study area. The first step was to describe the major structural features of the sub-basin, based on time-structure contour maps of the bases of the Winduck, Snake Cave and Ravendale Intervals. The second step involved comparison of the time-structure maps with the most recently available gravity data of the area, compiled by the New South Wales Department of Mineral Resources in 2003 (Figure 2). A good correlation was observed between the gravity data and the two-way travel time contours to the

key horizons, especially those on the base of the Winduck Interval. This indicates that the gravity data mainly reflect the sub-basin structure, and do not appear to be significantly affected by variations in basement density or rock type. The third step was to compare the isochore map for each lithostratigraphic unit (in terms of two-way travel time) to the time-structure patterns, especially for the Winduck and Snake Cave Intervals. The fourth step was to interpret the tectonostratigraphic evolution of the area, as indicated by a study of the contour maps and a closer look at the individual seismic cross-sections. This suggested a history involving three separate phases of tectonic activity.

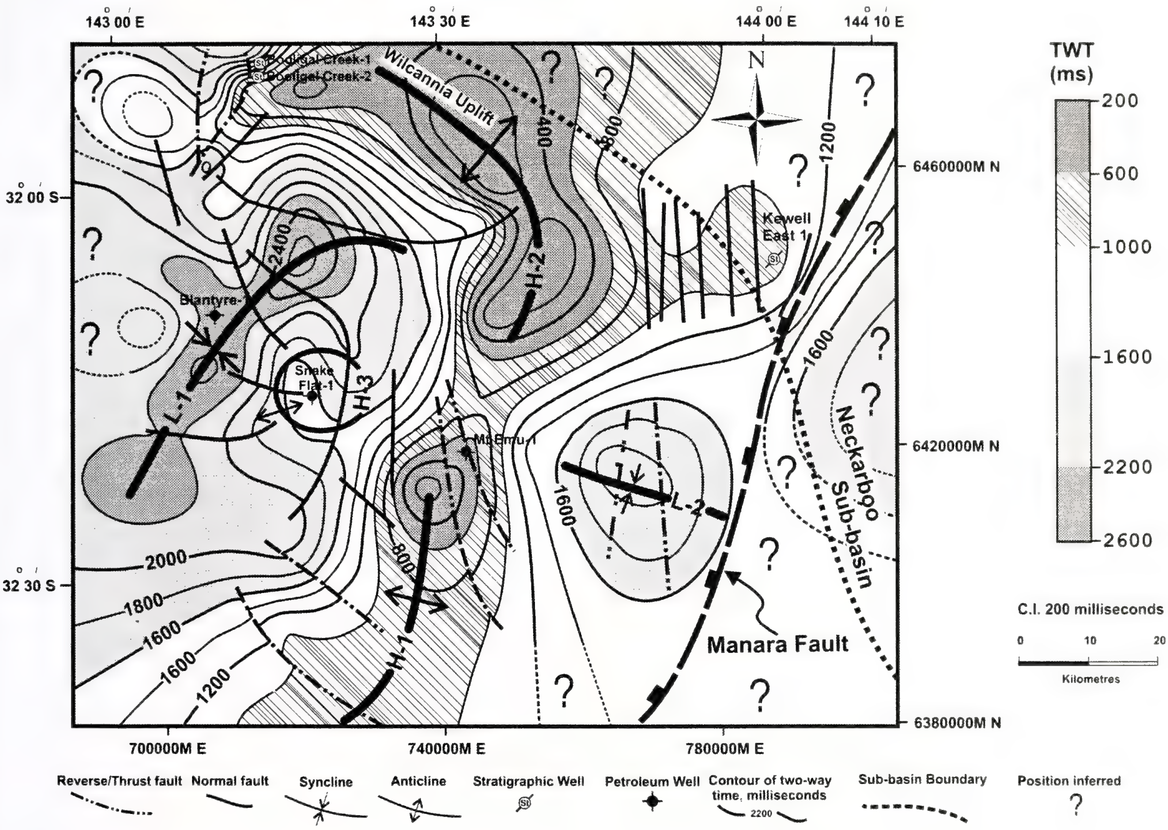

Figure 3. Two-way time structure map of the base of the Winduck Interval within the Blantyre Sub-basin showing hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as discussed in the text.

RESULTS AND DISCUSSION

Subsurface Map Construction

On the basis of the interpretation of the newly acquired data, the Blantyre Sub-basin can now be divided into a number of distinct structural provinces; these provinces are shown in the three two-way time structure maps (Figures 3, 4 and 5), supplemented by the two isochore maps (Figures 6 and 7).

Structure Map Interpretation

The data analysed includes both stratigraphic and seismic data. The three two-way time structure maps interpretations in Figures 3, 4 and 5 are consistent with a reconstructed pattern of sub-basin evolution.

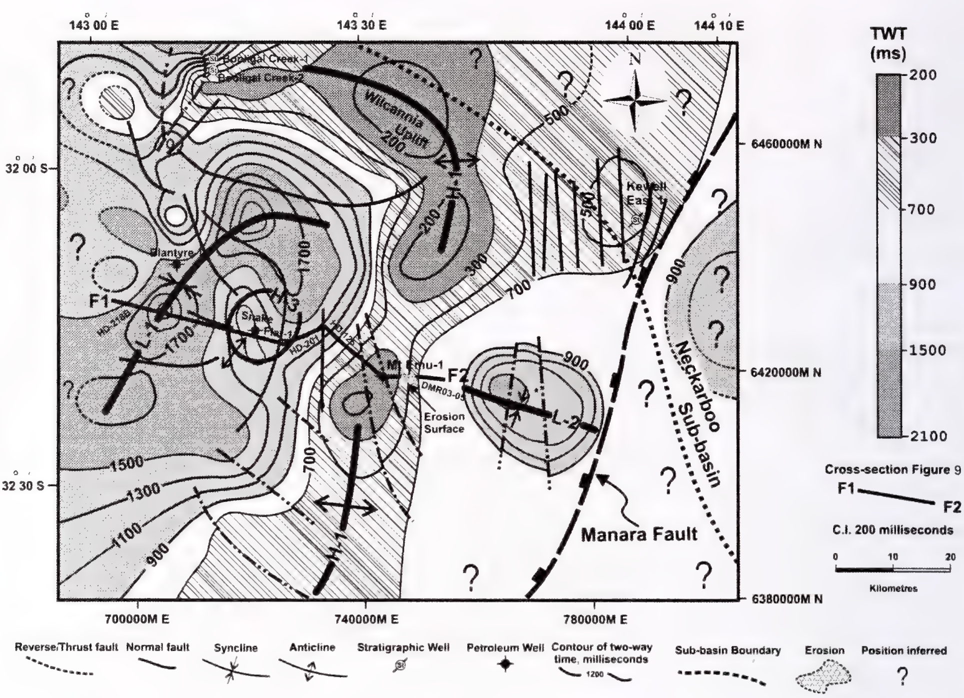

Figure 4. Two-way time structure map of the base of the Snake Cave Interval within the Blantyre Sub-basin showing hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as discussed in the text.

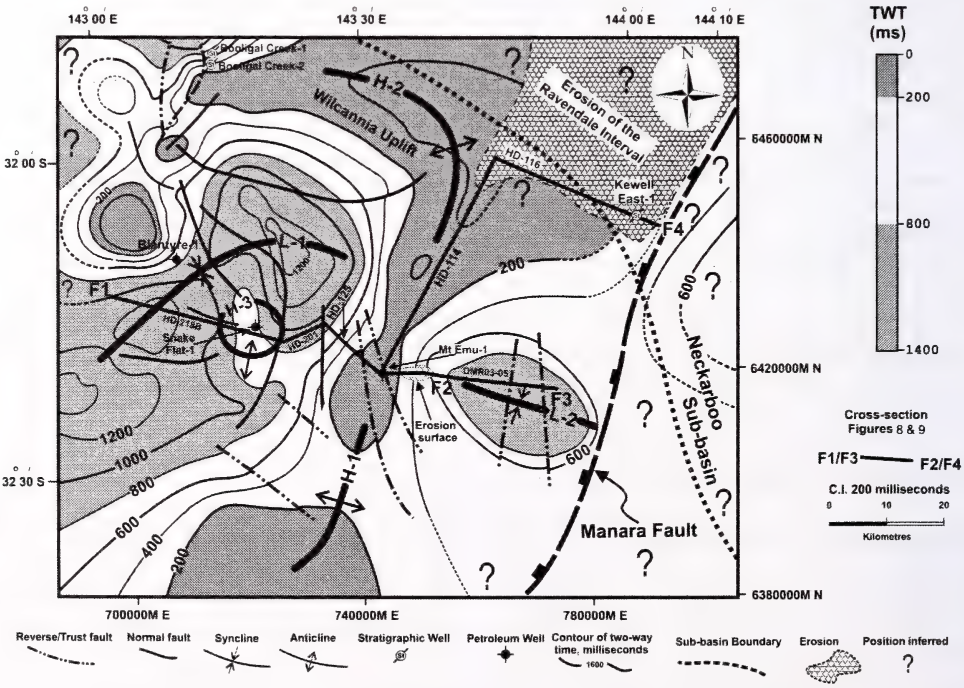

Figure 5. Two-way time structure map of the base of the Ravendale Interval within the Blantyre Sub-basin showing hinge surface traces of structural highs (anticlines H-1, H-2 and dome H-3) and structural lows (synclines L-1 and L-2) and the Manara Fault as discussed in the text.

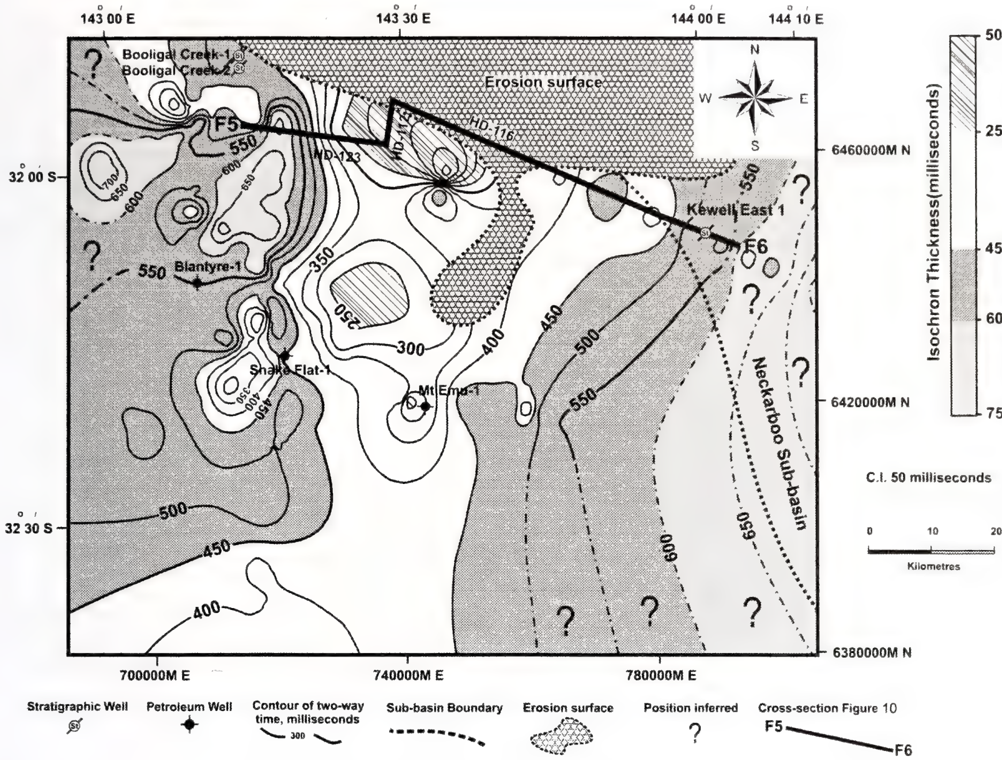

Figure 6. Isochore map of the Winduck Interval, showing the response of the latest Silurian to late Early Devonian sequence to subsidence within the Blantyre Sub-basin.

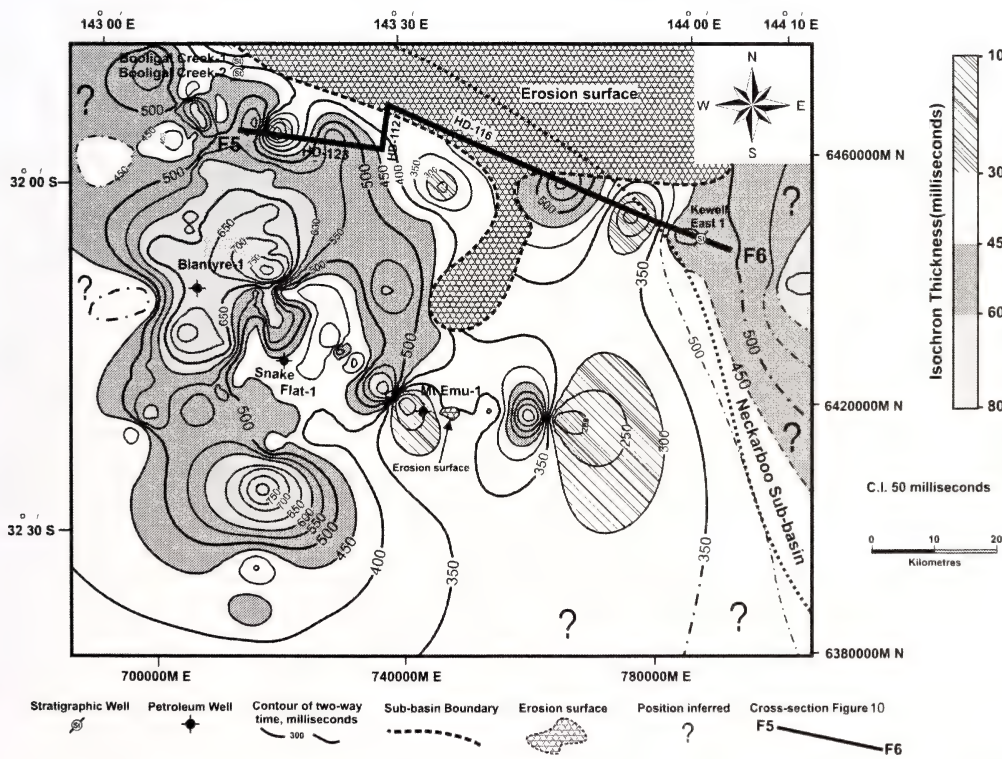

Figure 7. Isochore map of the Snake Cave Interval, showing the response of the late Early Devonian to early Middle Devonian sequence to subsidence within the Blantyre Sub-basin.

(A) Two-way time structure contours on base of Winduck Interval

The two-way time structure contours on the base of the Winduck Interval (Figure 3) shows a NE-SW oriented structural low (L-1) in the western part of the Blantyre Sub-basin, centred around the Blantyre-1 exploration well. To the east of this is a NE-SW trending high, lying approximately along seismic profile SS134>HD-114. This contains two smaller high areas, one of which (H-1) is immediately SW of the Mount Emu-1 site.

The base of the Winduck Interval is widespread throughout the Blantyre Sub-basin. Its depth ranges between 200 to 2600 milliseconds of two-way travel time, being shallowest near the northern margin and deepest in the faulted central part of the Blantyre Sub-basin (Figure 3). The strata of the Winduck Interval, as defined from seismic profile DMR03-05, have an estimated thickness in this area of approximately 1,400 metres (Figure 8).

Farther east again there is a second structural low (L-2), centred near the eastern end of seismic profile DMR03-05. The eastern part of this structure is poorly defined, due to a lack of seismic coverage. However at the eastern end of DMR03-05 there is an up-to-the-east high angle reverse fault (see Figure 9). A second structural high (H-2) is mapped in the northern part of the Blantyre Sub-basin, running east and then SE from Booligal Creek-1 and Booligal Creek-2 (Figure 2). This corresponds to the feature identified by Evans (1977), Alder et al. (1998), Pearson (2003), Neef (2005), Cooney and Mantaring (2007) Khalifa (2005) and Khalifa and Ward (2009) as the Wilcannia High. It curves southwards to link up with the NE-SW high (H-1) through the Mount Emu-1 well site. Smaller structural highs are noted west of the Booligal Creek wells, east of the Wilcannia High around the Kewell East well, and west of the main NE-SW high, around the Snake Flat well (H-3) (see Figures 2 and 3).

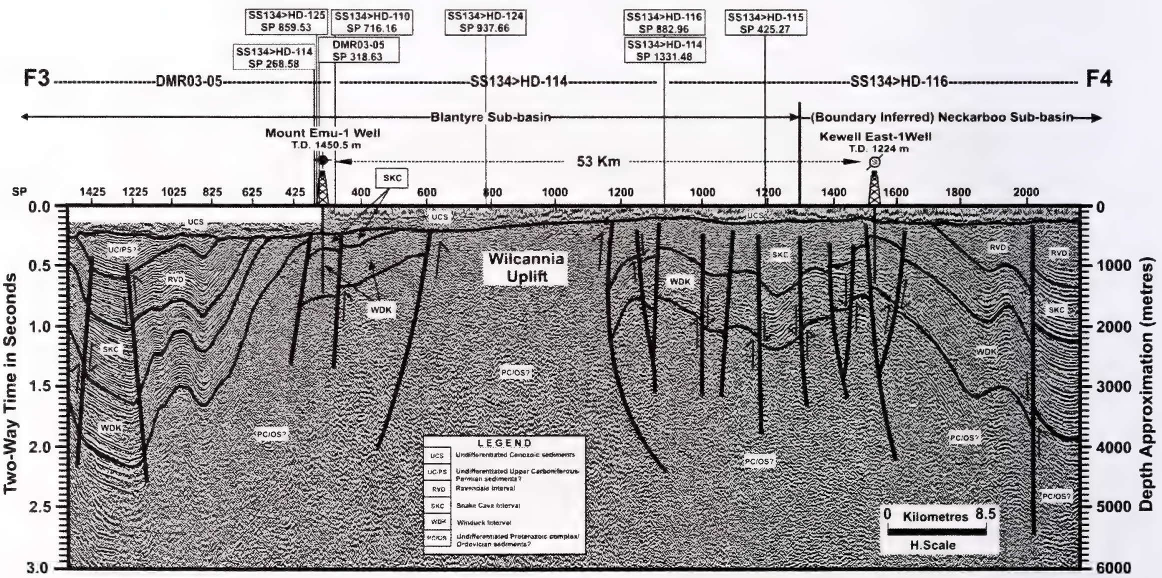

Figure 8. Interpreted seismic section F3-F4, through east part of the Blantyre Sub-basin linked to the Neckarboo Sub-basin showing how thickening of Winduck, Snake Cave and Ravendale Intervals is compartmentalized on either side of the Wilcannia Uplift by complex faults. Section is based on well data, gravity data, and seismic profiles SS134>HD-114, 116 and DMR03-05. Location of seismic section is shown in Figure 5.

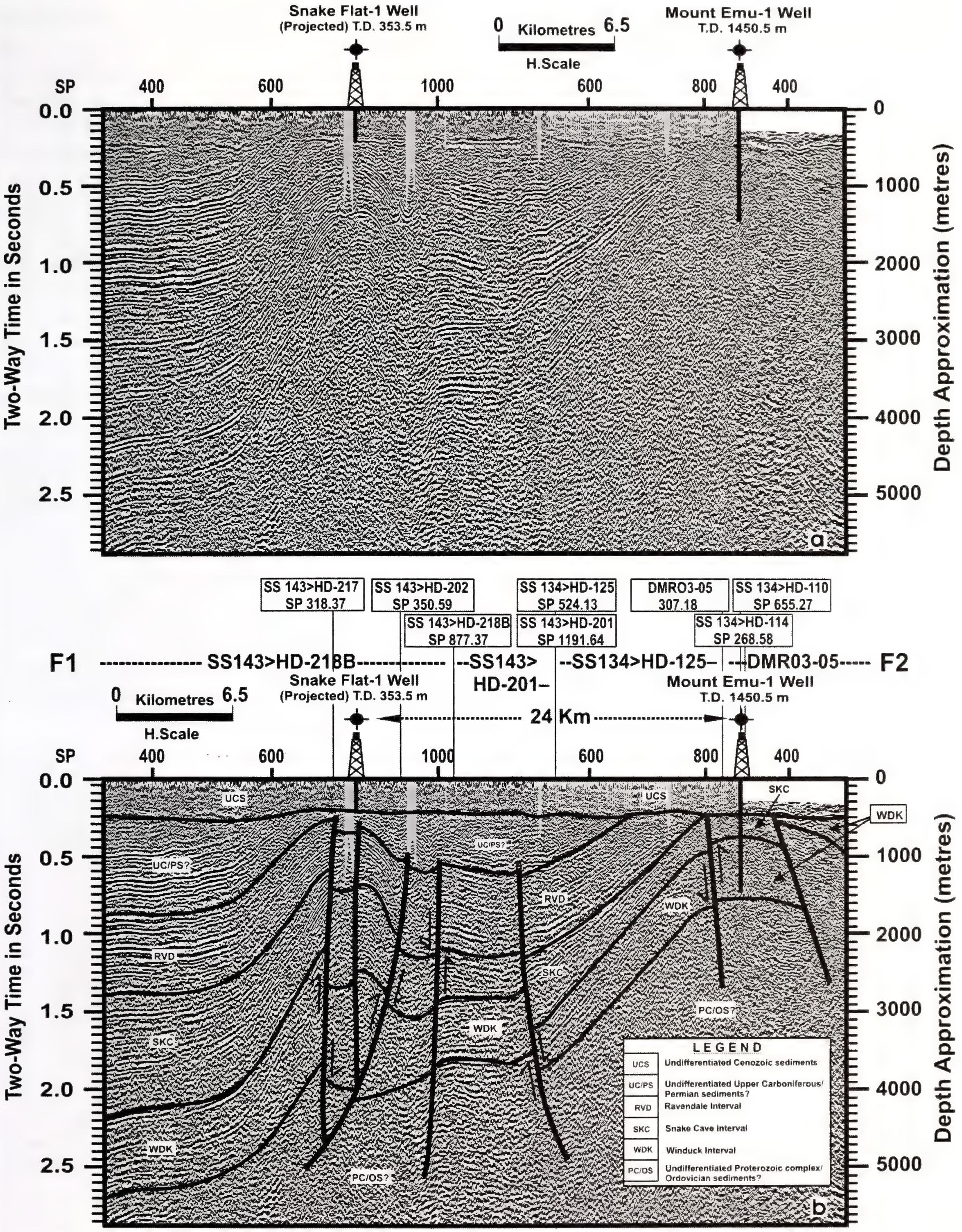

Figure 9. (a) Uninterpreted seismic section F1-F2 through the central part of the Blantyre Sub-basin, showing location of seismic section as shown in Figures 4 and 5 (b) Interpreted seismic profiles SS143>HD-218B and 201 showing the most deformed part of Snake Flat anticline with several high angle reverse faults. Also interpreted part of seismic profiles SS134>HD-125 and DMR03-05, showing anticlinal folding and a associated thrust fault, indicating stratigraphic geometry and absence of the Ravendale Interval in the Mount Emu-1 well.

(B) Two-way time structure contours on base of Snake Cave Interval

The two-way time structure contours on the base of the Snake Cave Interval (Figure 4) display a similar structural pattern to those on the base of the Winduck Interval (Figure 3). The surface for the base of the Snake Cave Interval has been mapped using data from all of the available shot points on the seismic profiles in Figure 2, except where the unit has been completely removed by erosion. Figure 9 displays a part of seismic profiles SS134>HD-125 and DMR03-05, which indicate in greater detail the setting of the anticlinal folding and associated thrust faulting close to the Mount Emu-1 Well. Figure 3 also shows a NE-SW oriented structural high (H-1) around the Mount Emu-1 Well, representing the Mount Emu Anticline (cf. Mullard 1995, Khalifa 2005).

The base of the Snake Cave Interval recognised in the two-way time structure contours within the Blantyre Sub-basin, ranges in depth between 200 and 2100 milliseconds of two-way time, being shallowest near the northern margin of the sub-basin and deepest in the faulted region in the central part of the study area (Figure 4).

The strata of the Snake Cave Interval, as shown in Figures 8 and 9, has been mapped by combining information from seismic profiles and well logs. In the wells, the greatest known thickness of the Snake Cave Interval (243.1 metres) has been recorded in Mount Emu-1 (cf. Khalifa 2005, Khalifa and Ward 2009), and the minimum thickness (about 100 metres) in Blantyre-1 (cf. Bembrick 1997b) is shown in Table 1, but thickness reaches an estimated 1,600 metres in the western Blantyre Sub-basin (e.g., at about 1.4–2.2 sec. TWT around SP 400 in seismic profile SS143>HD-218B; Figure 9).

(C) Two-way time structure contours on base of Ravendale Interval

The two-way time structure contours on the base of the Ravendale Interval (top of Snake Cave Interval) show a similar pattern to Winduck Interval and Snake Cave Interval although there are extensive areas where the Ravendale Interval is not present (Figure 5). The Wilcannia High in the northern part of the sub-basin clearly exposed the Ravendale Interval, running SE from the Booligal Creek-1 and Booligal Creek-2 wells. The Wilcannia High is also seen to curve southwards and link up with the NE-SW oriented structural high (H-1) controlled by the Mount Emu Anticline (Figure 9).

The base of the Ravendale Interval is widespread throughout the Blantyre Sub-basin, at a depth ranging from 250 to 1400 milliseconds of two-way travel time. It is shallowest in the southeastern and northern parts of the sub-basin, and deepest in the faulted region in the central part of the study area (Figure 5). The Ravendale Interval is absent in the Mount Emu-1, Snake Flat-1, Booligal Creek-1, and Booligal Creek-2 well sections (Table 1). The strata of the Ravendale Interval reach a maximum thickness of approximately 1200 metres in the western Blantyre Sub-basin (e.g., at about 0.6–1.1 sec. TWT between SP 600 and 1000 in seismic profile SS143>HD-201, Figure 9).

The base of the Ravendale Interval is missing in part of the area (Figure 5), especially in the north-east, due to erosion after deposition and uplift. This is also shown on seismic section F3-F4 (Figure 8).

Integration of Data from Structure Contour and Gravity Structure Maps

The gravity contours of the area can be compared with the two-way travel time contours on the base of the Winduck Interval (Figures 2 and 3). The gravity data also reflect the main structural features indicated on the two-way time structure contour maps. Two gravity lows, with NE-SW orientations are interpreted in the western part of the sub-basin, and a NW-SE oriented structural low occur near the eastern end of seismic profile DMR03-05. These correspond to positive structures on the travel-time contour map of the base of the Winduck Interval (Figure 3).

A positive gravity anomaly, corresponding to the Wilcannia High, is clearly identified on the northern margin of the Blantyre Sub-basin, around the Booligal Creek-1 and Booligal Creek-2 wells. This appears to link with

gravity high (H-1) through the Mount Emu-1 well (equivalent to the Mount Emu anticline in Figure 9). The NE-SW oriented structural high around the Snake Flat-1 well corresponds to a similar structure inferred from the travel-time structure map (Figure 3) at the base the Winduck Interval. Further detail of the structural high (H-3) around the Snake Flat-1 Well, representing the Snake Flat Anticline (cf. Mullard 1995, Khalifa 2005), is shown in Figure 9. This is the most deformed part of the anticline, and is marked by a high angle reverse fault and an asymmetrical fold.

Comparison of Structure Contour and Isochore Maps

Isochore maps have been constructed for the Devonian sequence in the Blantyre Sub-basin, based on the seismic data. The units evaluated were of the Snake Cave and Winduck Intervals.

(A) Thickness of the Ravendale Interval

The thickness of the Ravendale Interval in many parts of the Blantyre Sub-basin is incomplete, due to removal of strata by erosion following uplift associated with the faults and folds that have deformed the strata since deposition (e.g. seismic section F5-F6, Figure 10). This and other sections have been used to identify those parts of the region where the Ravendale Interval, and in some cases other units, are partly or completely removed by post-structure erosion, and to separate those areas from areas with the full (un-eroded) interval thickness.

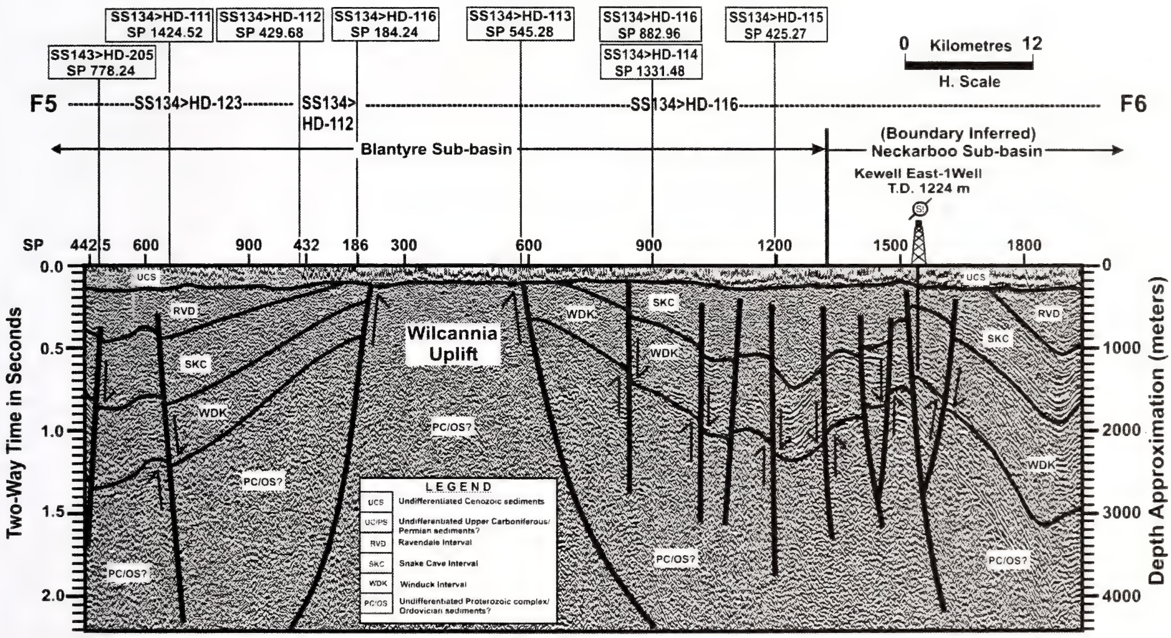

Figure 10. Interpreted seismic section F5-F6, showing the geometry of the tectonic and stratigraphic units within the Blantyre Sub-basin across the Wilcannia Uplift. Cross-section is based on well data, gravity data and seismic profiles SS134>HD-123, 112 and 116. See Figures 6 and 7 for location of seismic section F5-F6.

(B) Thickness of the Snake Cave and Winduck Intervals

The isochore maps for the Winduck and Snake Cave Intervals (Figures 6 and 7) show a broad similarity to the structure contour maps of their boundary horizons (Figures 3 and 4), with some degree of thickening and thinning in areas where the travel-time structure contours show low and high elevations respectively.

The structure contour map on the base of the Winduck Interval (Figure 3) indicates structural lows, or synclinal areas, along the sub-basin axis (a NE-SW oriented feature identified as L-1 and a NW-SE oriented feature identified as L-2), and the corresponding thickness variations (Figure 6) indicate that these areas subsided more rapidly during Winduck Interval deposition. Similar structural lows or synclinal areas are observed by thickening in the isochore map of the Snake Cave Interval (Figure 7), although the extent is more limited due to erosion of the unit within the sub-basin (Figure 6). Nevertheless, there are clear increases in thickness of the Winduck and Snake Cave Intervals from near the western and eastern edges of the Blantyre Sub-basin towards its centre.

Figure 10 shows thinning of the Winduck and Snake Cave Intervals on to the Wilcannia High in the west in seismic section F5-F6, and a remarkable thickening of the late Early Devonian to early Middle Devonian Snake Cave Interval in the Blantyre Sub-basin to the east of this structure, towards the Kewell East-1 well. It also indicates that the base of the Ravendale is present farther to the east, around shot point 1800 on seismic profile SS134>HD-116, where the Snake Cave Interval is again of more 'normal' thickness.

Figure 9 illustrates the stratigraphic and present-day structural configuration of the Blantyre Sub-basin. Lithostratigraphic unit relationships within the east-central Blantyre Sub-basin are similar to those in the west-central portion of the study area.

Although the nature of the sequence is poorly documented due to limited well penetration, the Winduck Interval and the Mulga Downs Group (Snake Cave and Ravendale Intervals) show little variation in thickness, suggesting tectonic quiescence within the region during the period of sediment accumulation. The most prominent feature is the alternate thickening and thinning of the area adjacent to the faults identified by this study in regional seismic sections, F3-F4 and F5-F6 (Figures 8 and 10). However, the characteristics of the Winduck, Snake Cave and Ravendale Intervals are particularly evident where sequences are thicker, in the central part of the section (between SP 400 and 800, Figure 9). They gradually disappear where the Winduck and Snake Cave Intervals become thinner, near the Wilcannia High, close to the northern margin of the sub-basin, for example between shot points 186 to 432 in seismic profile SS134>HD-112 (Figure 10).

Tectonstratigraphic Evolution of the Blantyre Sub-basin

Figures 11 and 12 provide a simplified reconstruction of the deformation history for the Winduck, Snake Cave and Ravendale tectonostratigraphic packages within the Blantyre Sub-basin. Four stages of tectonic evolution are suggested for the study area: (a) rapid subsidence, (b) compression associated with continued subsidence (Tabberabberan Event) (c) compression associated with uplift and erosion (Alice Springs/Kanimblan Event) and (d) extension associated with slow subsidence.

Cross-section through the Mount Emu High

Cross-section T1-T2 (Figure 11) represents a section across the Mount Emu-1 well, extending from seismic profile DMR03-05 near structural low L-2 (Figure 3) through the Mount Emu anticline, and north-east to seismic profile SS134>HD-125 and the end of seismic profile SS143>HD-204 (for location see Figure 2). High subsidence rates are interpreted during deposition of the Winduck, Snake Cave and Ravendale Intervals over the two low areas (i.e. the two ends of cross-section T1-T2), and lesser subsidence rates (smaller thicknesses) across the structural high (i.e. the Mount Emu anticline).

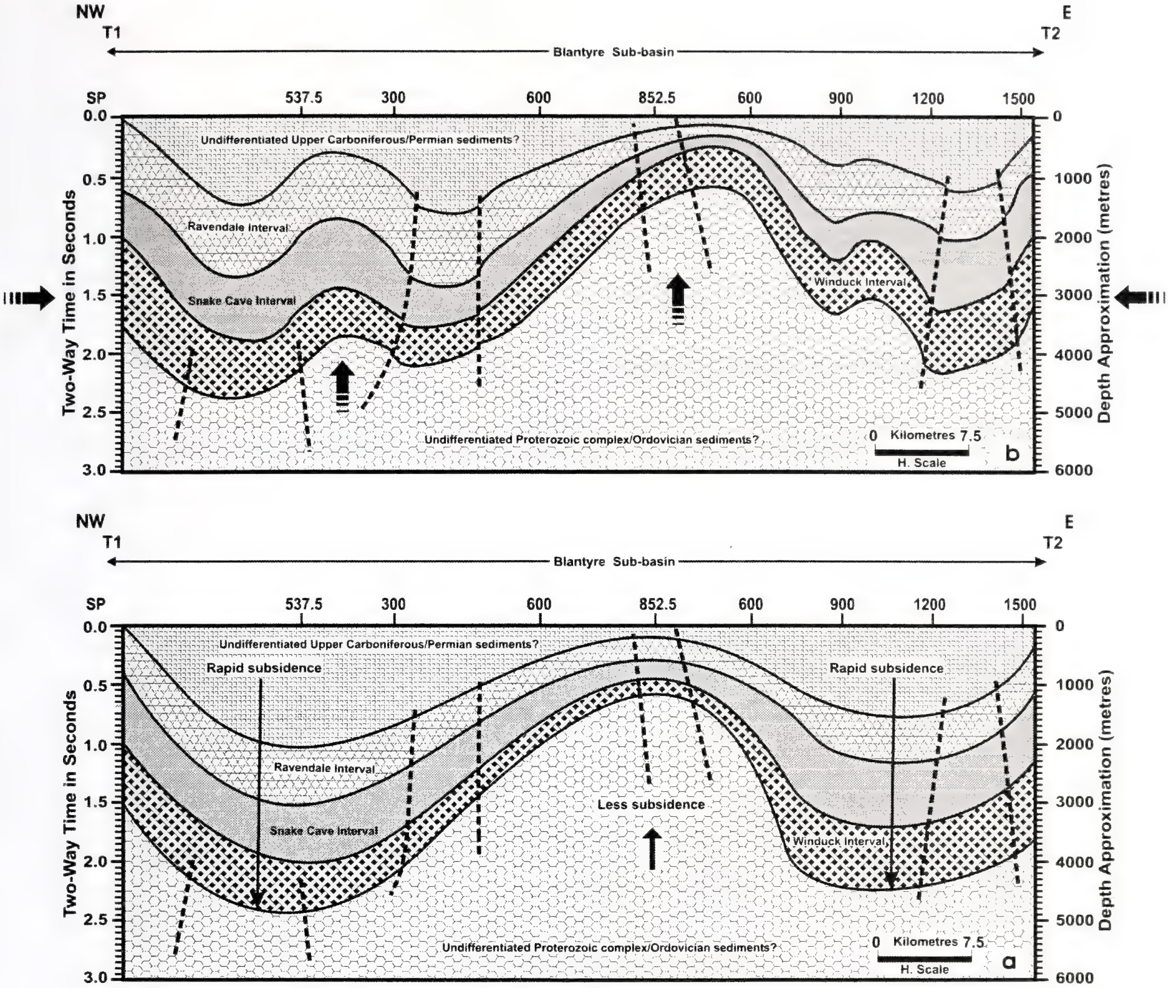

Figure 11 a & b. Cross-section T1-T2, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (a) High subsidence rates in the trough areas (b) Compression and localized deformation associated with subsidence. (Figure 11c & d on next page.)

Figure 11a represents a schematic reconstruction of the section during the rapid subsidence phase of basin development. The Winduck and the Snake Cave Intervals are of similar thickness in the two synclinal areas. However, the Ravendale Interval appears from seismic data, where a complete section is preserved, to be thinner in the synclinal area east of the Mount Emu High.

Compressive deformation then gave rise to folding in the synclinal areas (Figure 11b, c), and reverse faulting developed at several locations associated with both the synclinal and anticlinal areas. Additional downwarping occurred in the synclinal areas, and additional uplift on the intervening basement highs.

Regional uplift and erosion possibly associated with relaxation of the compressive stresses and development of the extensional regime, gave rise to the present-day structure of the sub-basin (Figure 11d). Cenozoic sediments were late deposited on the deformed Darling Basin units during the slower subsidence associated with this extensional phase.

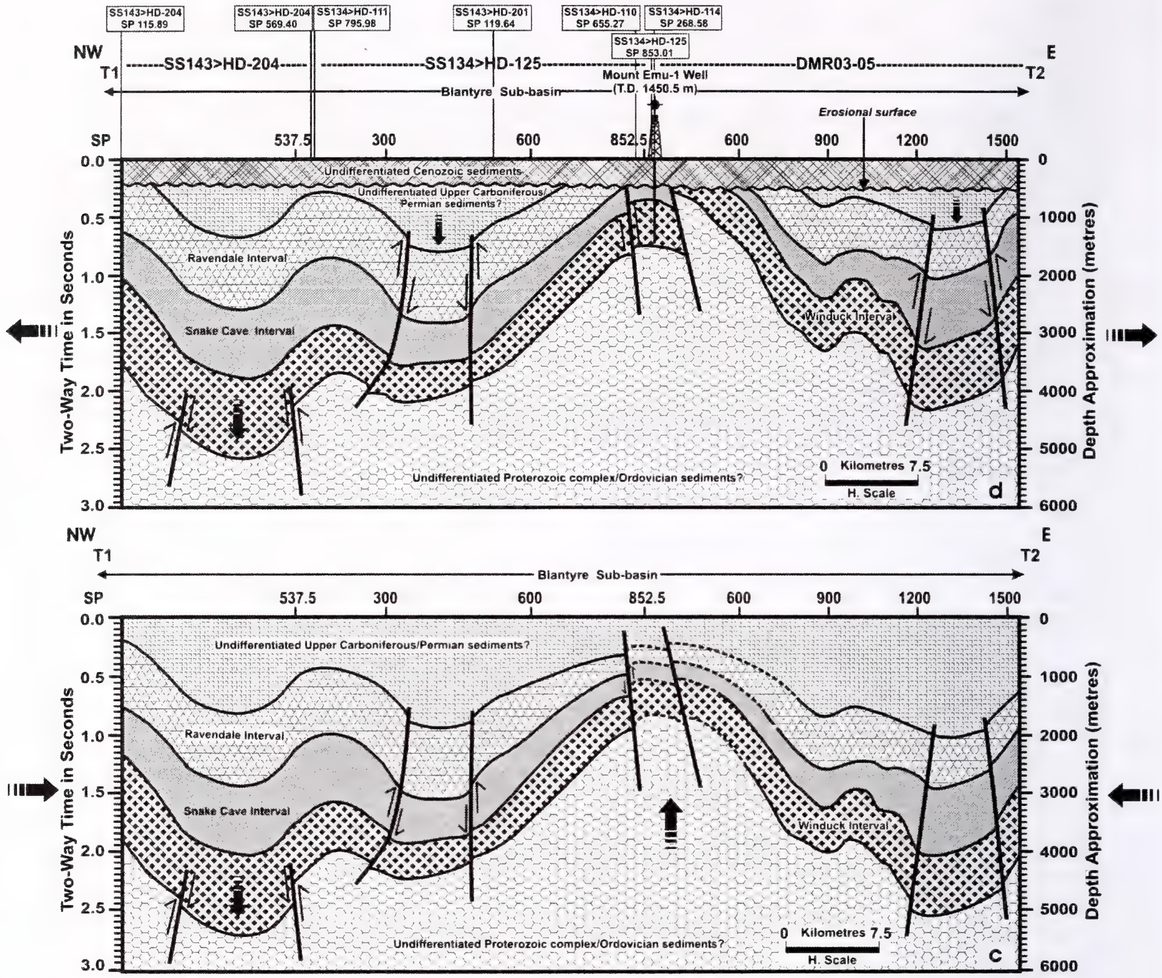

Figure 11 c & d. Cross-section T1-T2, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (c) More compression, showing further anticlinal folding associated with the Mount Emu structure to create complex reverse faults (d) Further development of the Mount Emu thrust fault, followed by extension, erosion and deposition of the Cenozoic sediments.

Cross-section through the Wilcannia High

Cross-section T3-T4 (Figure 12) is a dip section across the Wilcannia High, extending from the Kewell East-1 well in the east (part of the Neckarboo Sub-basin) through seismic profile SS134>HD-116 and part of seismic profile SS134>HD-114 (between shot points 937.66 to 1331.48), as shown in Figure 2, to the end of seismic profile SS134>HD-124.

Figure 12a represents a schematic reconstruction of the section during the rapid subsidence phase of sub-basin development. Lower subsidence rates are interpreted across the high area in the central part of cross-section T3-T4 during deposition of the Winduck, Snake Cave and Ravendale Intervals (Figure 12a). Higher subsidence rates during Winduck, Snake Cave and Ravendale deposition are interpreted in the trough area farther to the west on the same cross-section.

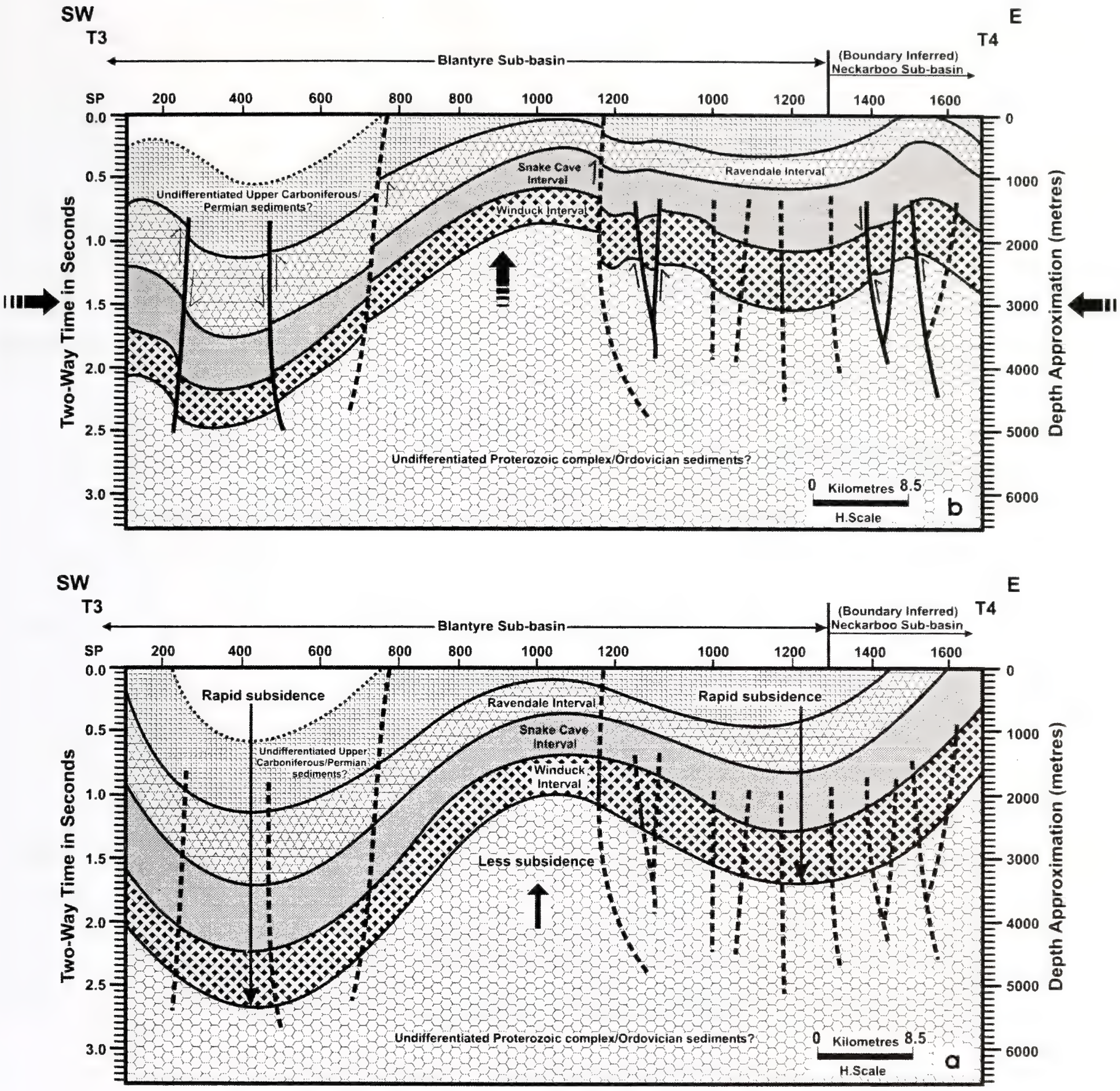

Figure 12 a & b. Cross-section T3-T4, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (a) High subsidence rates in the trough areas (b) Compression and localized deformation associated with further subsidence, especially in the southwest. (Figure 12 c & d on next page.)

The lithostratigraphic units representing the Winduck, Snake Cave and Ravendale Intervals are of similar thickness in the two synclinal areas, but the three tectonostratigraphic packages appear from the seismic data, where a complete section is preserved, to be thinner on the Wilcannia High itself, for example around shot points 1000 to 1200 on cross-section T3-T4 (Figure 12a).

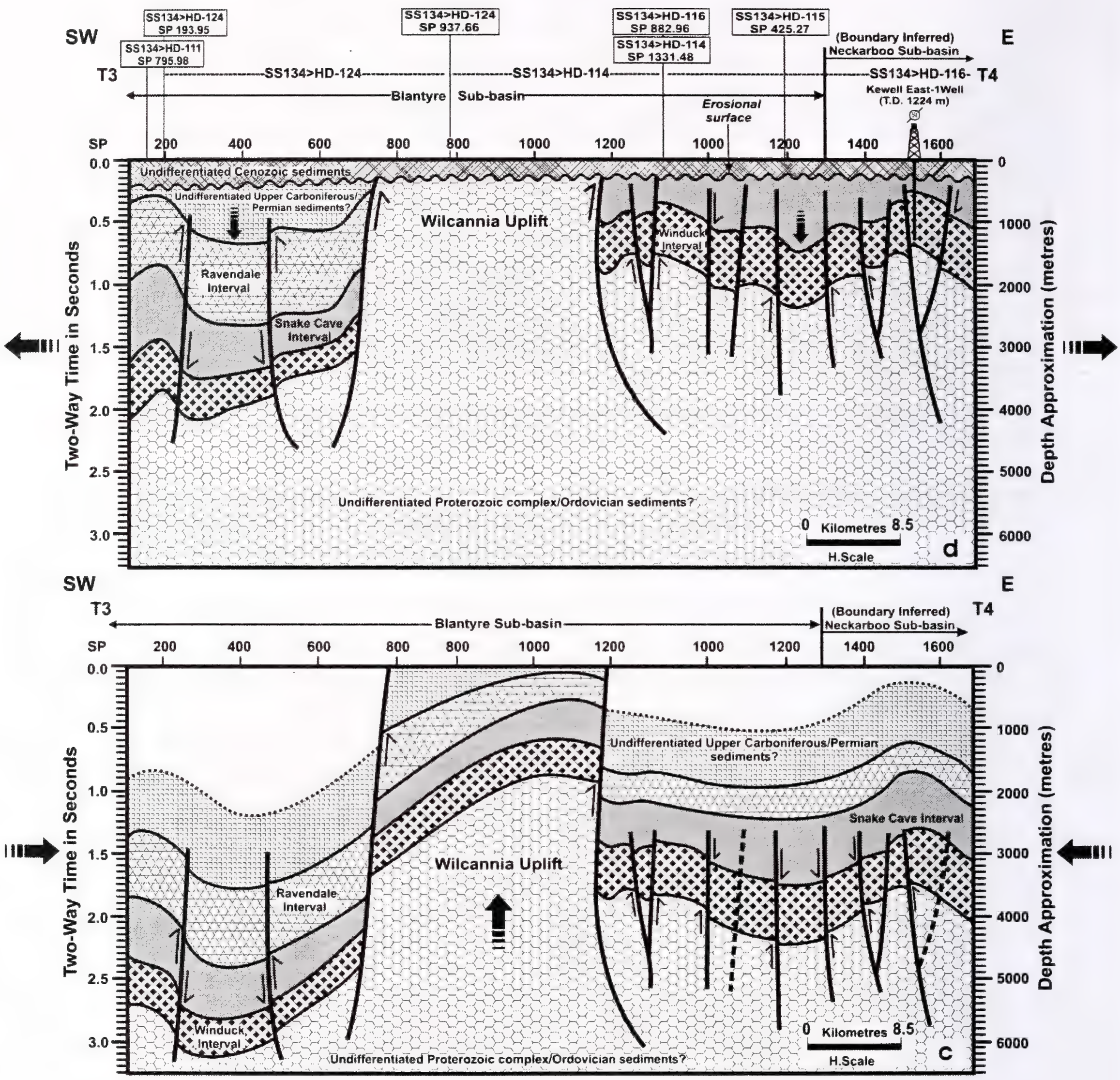

Figure 12 c & d. Cross-section T3-T4, showing the tectonic development of the Blantyre Sub-basin (See location of cross-section in Figure 2). (c) More compression with maximum movement of the Wilcannia Uplift contrast in complex thrust and normal-faults in the east (d) Extension, enhancement of horst-graben structures, erosion and deposition of the Cenozoic sediments.

Figure 12b shows a reconstruction of the highly faulted area on the eastern end of section T3-T4, suggesting that major subsidence occurred around the eastern margin of the Blantyre and the western margin of the Neckarboo Sub-basins. The more structurally complex zone of normal and reverse faults in between the sub-basins is associated with later compression forming a relatively symmetrical synclinal fold. Figure 12c suggests that, by the end of the second tectonic stage, the Wilcannia Uplift had begun to develop in the area, with the Winduck, Snake Cave and Ravendale Intervals being partly or completely removed by post-structure erosion. The extent of erosion of the Ravendale Interval is further indicated in Figure 5.

The last stage of tectonic development represents extension, enhancement of the fault structures, regional uplift, erosion and deposition of the Cenozoic sediments over the whole of the Blantyre Sub-basin. However, Figure 12d shows extension with faults after the Devonian, and then deposition of the overlying Upper Carboniferous/Permian sediments during a tectonically quiet period with broad slower subsidence. Cenozoic sediments were deposited over the whole section following erosion.

The high on the eastern side of cross-section T3-T4 is part of the Kewell East Anticline, bounded on the west side by fault zones (complex of normal and reverse faults) and a near symmetric synclinal fold (Figure 12d). This high was drilled by the Kewell East-1 well (Clark et al. 2001).

Basement Surface

A change in basement dip is evident on regional seismic sections across kilometer-scale wavelength fold structures (e.g. Mount Emu and Snake Flat anticlines) and a basement 'pop-up' feature that was formed in post-Devonian time. Also shown on the regional sections that integrate the gravity data and the seismic profiles (Figures 11 and 12) is a strong onlap and thinning of the Winduck and Snake Cave Interval on to palaeo-basement highs, indicating that many of the present sub-surface highs were highs during sediment deposition. However, the faults bounding these paleo-highs had northwest-southeast, east-west and north-south strike orientations, supporting a suggestion that all of these fault systems were co-active during the extensional part of the sub-basin history and controlled differential subsidence. Similarly, 'palaeo-basement' character is inferred for the Mount Jack High and the Lake Wintlow Highs by Glen et al. (1996), Alder et al. (1998), Willcox et al. (2003) and Cooney and Mantaring (2007).

The basement structure may have influenced thickness variations in the Winduck and Snake Cave Interval. There are hints of this on the seismic data, where the basal Winduck Interval is interpreted to be faulted or gently warped (Figures 11 and 12). In turn, the shape and thickness of the Winduck Interval may have influenced fold development, such as across the Mount Emu anticlinal fold. In contrast, for areas to the northwest and southeast, gravity lows do correspond to basement depth estimated from seismic profiles SS134>HD-123, 124, SS143>HD-204, 218B and DMR03-05 (Figure 2).

Structural Aspects and Implications for Hydrocarbon Potential

The hydrocarbon potential of the Darling Basin has been discussed by Evans (1977), Brown et al. (1982), Byrnes (1985), Bembrick (1997a, b) and Wilcox et al. (2003), and described in more detail by Alder et al. (1998), Pearson (2003), Cooney and Mantaring (2007), Khalifa (2005), and Khalifa and Ward (2009). Herein, I summarize the specific structural aspects of the hydrocarbon potential prospects in the Blantyre Sub-basin related to the folding and associated complex faulting that have affected the latest Silurian-Devonian stratigraphic geometry.

The anticlinal crests of Snake Flat, Mount Emu and Kewell East folds are the primary targets for any future exploration (Figures 8 and 9), with additional potential for stratigraphic pitch-out plays on the flanks of some structures. Individual structures have areal closure of up 100 square kilometres, with more than 2000 metres of section under closure. The different models of fold formation described in this paper would influence any prospects. A tectonostratigraphic model of anticlinal geometry is assumed to have developed, as the fold translated over a fault, bending would predict a repetition of the deep section within the core of the fold structure. The fracture patterns predicted by the tectonostratigraphic model (Figures 11 and 12) also would be quite different, an important point considering that fracture permeability may play a significant role in developing viable hydrocarbon targets across the folds. The extent of these major folds beneath the Upper Carboniferous/Permian sediment and their possible hydrocarbon potential are important unanswered questions in the Blantyre Sub-basin.

CONCLUSIONS

This paper has attempted to integrate the data from the seismic profiles, several maps and wells into a consistent geologic picture, in order to add some new insights into the structural styles and tectonostratigraphic framework of the Blantyre Sub-basin.

A geological model has been derived from interpretation of two-way travel time structure contour maps, in conjunction with the regional gravity contour map. Several major structures have been identified and named. These include a large structure situated at the junction of three major high complexes, referred to as the Wilcannia High (H-2), and two smaller high areas. One of these, the Mount Emu High (H-1), is an anticlinal fold with thrust fault; the other, the Snake Flat High (H-3), is an asymmetric anticlinal fold with a number of high angle reverse faults. Two structural lows have also been identified, aided by correlations between the structure contour data and the gravity map, especially the structure contours on the base of the Winduck Interval. In the central part of the Blantyre Sub-basin, around the Blantyre-1 exploration well, there is a structural low (L-1). This is an elongate, synclinal fold, and covers an area of approximately 400 square kilometres. There is a second generally smooth structural low (L-2) within the Blantyre Sub-basin. This is also shown on the gravity contour map and the structure contour map on the base of the Winduck Interval, and is seen on seismic profile DMR03-05.

Isochore maps for each stratigraphic interval (in two-way travel time) have been compared with the travel-time structure contour patterns, especially for the Winduck and Snake Cave Intervals, to identify any thickening and thinning associated with structural development. Improved isochore maps will provide control for structure mapped on seismic profiles, especially the Wilcannia, Mount Emu and Snake Flat structural highs. Key seismic cross-sections, T1-T2 and T3-T4, were also constructed to assist the analysis process, and further investigation of relationships between the tectonostratigraphic sequences, sub-basin geometry, and the development of complex structures within the study area.

The following broad history has been identified from these interpretations and a review of the basin's tectonic evolution: (a) high subsidence rates in the trough areas, (b) compression and localized deformation associated with further subsidence, (c) extension, enhancement of normal and reverse faults, including the Wilcannia Uplift and (d) erosion and deposition of the undifferentiated Permo-Carboniferous, Early Cretaceous and Cenozoic (Tertiary and Quaternary) sediments, identified at shallow depths within the main Blantyre Sub-basin.

A tectonostratigraphic model has been put forward to address the variation in compressional and extensional fault and fold-related stresses that created the observed differences in the deformation of the original normal and reverse faults, and the synclinal and anticlinal fold structures. The positive subsidence patterns are always fault-controlled, as shown in cross-sections T1-T2 and T3-T4 (Figures 11 and 12). Understanding the ongoing structural processes within interpreted seismic data should help to decrease the risk of hydrocarbon exploration by applying up-to-date concepts throughout the Blantyre Sub-basin.

ACKNOWLEDGMENTS

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APPENDICES

Summary of seismic data acquisition and processing parameters in the study area.

Date: 1984 by Seiscom Delta United Inc. Example: SS134>HD-114, 116, 123, 124, 125

ACQUISITION

1. Energy Source

Type:	Vibroseis Mertz Y-12
Source interval	60 metres
Sweep length	6 seconds
Sweep frequency	16–96 Hz upsweep
Source array	16 sweeps per station
Number of vibrators	4

2. Recording Geometry

Fold of recording	1200%
Geophone group length	33 metres
Spread	1980-100-SP-100-1980 metres
Number of groups	96 at 40 metres intervals

3. Instrumentation

Geophones	GSC HS 20D (10Hz) 12 per group
Filters:	Low cut OUT Hz slope dB/octave
	High cut 128 Hz slope 72 dB/octave
Record format	SEGY
Record length:	5 seconds
Sample interval:	2 milliseconds

PROCESSING

1. Initial Process:	Resample	4 milliseconds
	Trace edit	
2. Trace Equalisation:	Gate length	800 milliseconds
3. Datum Statics:	Static corrections	source and receiver elevations
	Datum	100 metres
	Replacement velocity	3000 meter/seconds
4. Velocity Analyses:	Velocities	Seiscom's Dove Velocity Spectra
	Computed	before and after DEWL
5. DEWL:	Surface consistent statics adjustment	
6. Trace Equalisation:	Gate length	500 milliseconds
7. Stack:	Type	Standard CDP
8. Bulk Shift:	-70 milliseconds	
9. Display System:	Type	Trace equalized
	Vertical scale	10 cm/sec
	Horizontal scale	10 traces/cm
	Peaks represent	Increase impedance

Continued on next page.

Date: 1985 by Seiscom Delta United Inc. Examples: SS143>201, 204 & 218B

ACQUISITION

1. Energy Source

Type	Vibroseis: Mertz Y - 12
Source interval	80 metres
Sweep length	6 seconds
Sweep frequency	16 – 75 Hz upsweep
Source array	16 sweeps per station
Number of vibrators	4

2. Recording Geometry

Fold of recording	2400%
Geophone group length	33 metres
Spread	1980 – 100 – SP – 100 – 1980 metres
Number of groups	96 at 40 metres intervals

3. Instrumentation

Geophones	GSC HS 20D (10Hz) 12 per group
Filters:	Low cut OUT Hz slope dB/octave
	High cut 128 Hz slope 72 dB/octave
Record format	SEGY
Record length:	5 seconds
Sample interval:	2 milliseconds

PROCESSING

1. Initial Process:	Resample	4 milliseconds
	Trace edit	
2. Trace Equalisation:	Gate length	800 milliseconds
3. Datum Statics:	Static corrections	source and receiver elevations
	Datum	100 metres
	Replacement velocity	3000 meter/seconds
4. Velocity Analyses:	Velocities	Seiscom's Dove Velocity Spectra
	Computed	before and after DEWL
5. DEWL:	Surface consistent statics adjustment	
6. Trace Equalisation:	Gate length	500 milliseconds
7. Stack:	Type	Standard CDP
8. Base Level Scaling:	9 window design	
9. Display System:	Type	Trace equalized
	Vertical scale	10 cm/sec
	Horizontal scale	10 traces/cm
	Peaks represent	Increase impedance

Continued on next page.

Date: 2003 by Trace Energy. Example: DMR03-05

ACQUISITION

Type	Vibroseis
Sweep frequency	5–90 Hz
Record length	6 seconds
Instruments	Sercel SN 388
Geophone group length	Sensor SM-4 LD SM-24
Sample rate	2 milliseconds
Record length	6 seconds
Filters:	Low cut OUT
	High cut 125 Hz
	Notch
Record format	SEGY
Spread	240 channel split spread
	Near offset - 12.5 metres
	Far offset - 2987.5 metres
Group spacing	25 metres
Shot spacing	25 metres

PROCESSING

Reformat	Input to promax internal format
Edit	Remove bad traces from shot record
Geometry	Set up shot and receiver co-ordinates
Filter	Zero to minimum phase filter
Deconvolution	Zero phase spectral whitening 5/7 - 90/110 Hz
	2 panels
Residual statics	Surface consistent residual statics calculated following structure.
	Window 1000 ms
	20 ms maxshift
Mute	First arrivals 30% stretch mute
Stack	CDP stack
	Data shifted to 122 metres datum
Filter	10 – 80 Hz filter
Scale	500 milliseconds AGC

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Quasars and Radio Galaxies

RAGBIR BHATHAL

Abstract

Richard Hunstead is one of thirty-three Australian Science Citation Laureates whose papers have been most frequently cited by other scientists around the world. His discovery of variability in radio sources of low frequencies generated a large number of related research projects internationally. He also conducted a seminal study of the evolution of the so-called Lyman alpha absorption forest in distant quasars in the mid-1980s, pioneering observations of quasar absorption lines at high spectral resolution and measurement of the heavy-element enrichment of galaxies at high redshift. He has been leading an international team to find the first massive galaxies to form. This study will provide insights into the formation of galaxies in the early universe.

Keywords: Quasars, Radio galaxies, Early universe

INTRODUCTION

He could have become a professional musician if he had wanted to be one but instead chose to become an astronomer to observe and probe the secrets of the music of the universe. His mother, Dagmar Roberts was a well known concert pianist and a child prodigy who began learning the piano at the age of three and won her first competition at the Drummoyne Eisteddfod five years later. In fact, at ninety-five years of age she may be the oldest student of the Sydney Conservatorium of Music. So the genes of music were already in him. 'I was quite good at the piano and competed successfully in Eisteddfods and on one occasion played on the radio in one of the children's programs.' At school he used to conduct 'the school choir and I actually composed a Christmas carol and conducted it when I was in my sixth class.' He had even been selected to play at the end of the year concert at Sydney Town Hall but according to him, 'unfortunately that never happened because I developed pneumonia and my substitute was Roger Woodward who went on to a career overseas and he is now back here as a teacher in Australia.'

INTEREST IN ASTRONOMY

In addition to his interest in music he was also interested in things mechanical. 'I liked to dismantle things and put them back together. I was interested in science but more in chemistry than in physics at high school.' He attended government schools. In fact, he attended a selective school (North Sydney Boys High School) for his secondary education which according to him had teachers who were 'genuinely interested in students.' At school he was also interested in photography and in order to process his photographs he converted the laundry at home in Turramurra into a darkroom. The skills he acquired in mucking around with things scientific and technical as a young boy were to come in handy when he went on to become an astronomer. His interest in astronomy came much 'later in high school' and crystallised at university when he came under the influence of Bernard Mills, the inventor of the Mills Cross and an extremely innovative radio astronomer (Mills 2006). 'While at high school', he said, 'he was aware of the growing field of radio astronomy that was getting a fair bit of publicity in the newspapers.' This was in the late 1950s when astronomers like Bernard Mills, Joseph Pawsey and Chris Christiansen were carving out a niche for Australia in the international world of astronomy (Bhathal 1996). He was about fifteen years old at that time.

SYDNEY UNIVERSITY

He went up to Sydney University for his undergraduate and postgraduate studies and surprisingly 'never left the place.' 'Although he was',

he said, 'near the top of the class for most of the time at North Sydney Boys High School', in his first year at university he found that there were 'lots of other very bright people'. He found this daunting particularly when he was exposed in 'my first lecture to Harry Messel. That sort of blew me away.' Messel, according to Hunstead, 'came across as a God-like figure, who had a booming voice and I perceived him to have very little tolerance for people who didn't understand what he was saying.' Messel was the Head of the School of Physics and was responsible for setting up the very successful Science Foundation for Physics. He was an extremely energetic and enthusiastic person who managed to persuade the captains of industry 'into contributing vast sums of money to the Foundation.' One of his great legacies was the creation of research groups and professorships in the School of Physics (Millar 1987). He persuaded Bernard Mills and Hanbury Brown to join the School of Physics. Both Mills and Hanbury Brown were extremely productive and innovative astronomers with international reputations.

For his honours year, Hunstead worked with Mills' radio astronomy group and did 'some work which ultimately was used in the construction of the Mills Cross telescope.' 'It was a way of steering the north-south arm of the telescope to minimize the amount of switching of delay lines that was necessary to steer it from the north horizon to the south horizon of the telescope. In those days a punch card was used to actually steer the telescope.'

After completing his honours in 1963 he went on to do his PhD under the supervision of Mills. His task was 'to look after the pointing calibration of the telescope. That is, how accurately could we determine the positions of the radio sources because our ultimate aim was to catalogue all of the strong radio sources. That was the principal driver for the Molonglo Cross telescope which operated at 408 Megahertz.' The Molonglo Cross telescope was built 30 kilometres east of Canberra near the township of Bungendore. He had to make frequent trips to collect data. He began during his PhD work to set about measuring the optical positions for a large number of counterparts of radio sources. According to him, 'this technique had not been used before on the Palomar Sky Survey plates and it was quite a pioneering study which made me somewhat notorious amongst traditional astronomers.' For carrying out his measurements he used a X-Y measuring machine which was designed by the CSIRO's National Measurement Laboratory and built in the School of Physics to very high technical standards. Apart from collecting the data on chart recorders it was also collected digitally. According to Hunstead, 'it was amongst the first digitally recorded data at a radio telescope.'

Before completing his PhD thesis he had already published eight papers in international journals. One paper in particular on the optical variable PKS 1514-24 was rather interesting (Hunstead 1971). It belonged to the category of BL Lac objects. It was the second known object in this class that he had discovered. It turned out not to be a star but a galaxy which showed enormous variability. He had drawn attention to a close agreement between a variable star called AP Lib and the Parkes radio source 1514-24. 'I had measured both the optical and radio positions for that object', he said. According to him, 'these very rapid variations are associated with the orientation of the radio jets in the case of radio emission and the optical accretion disc in the case of light emission that is more or less beamed directly towards us. Any small changes in direction can make big changes in the intensity of radiation we receive.'

QUASARS AND GALAXIES

Hunstead has carried out significant work in the fields of quasars and radio galaxies. According to Hunstead, 'quasars are the active cores of galaxies which have at their centres a super massive black hole with a mass of the order of a thousand million times the mass of the Sun which is actively accreting material from ripped up remnants of stars. The radio emission that we see is due to the very high energy particles that are generated in a accretion disc around a black hole'. 'The optical emission,' he continued, 'on the other hand is coming from the

accretion disc itself which is at a temperature of around 10 million degrees in these objects, which means it emits at wavelengths in the soft X-ray to extreme ultraviolet.'

While trying to establish the flux density calibration of the Molonglo telescope he found four variable radio sources at 408 Megahertz. He discovered that they shared something in common, viz: they were all identified optically with quasars. He saw these large variations at 408 Megahertz and 'didn't know what to make of this.' Astronomers at Arecibo and Jodrell Bank had also found some anomalies in their data but 'had thought nothing of it', he said. He published a paper in 1972 (Hunstead 1972) to show that 'the variations that we were seeing at 408 Megahertz didn't match at all with what we were seeing at high frequency' The paper not only triggered a lot of interest but also generated a number of PhD projects and observations at low frequency telescopes. 'All the low frequency telescopes around the world started looking at radio sources for variability. And a number of people that I've met subsequently have blamed me for giving them a PhD project which was to measure lots and lots of flux densities of radio sources. One of them was Jim Condon. Another one was Bill Cotton who works at the VLA.' Ten years later after his discovery a workshop was held on the topic (Cotton & Spangler 1982).

Three years later he wrote a paper on 3C 411, a newly discovered N galaxy with a large redshift (Spinrad, et al. 1975). At that time the connection between radio galaxies and quasars had not been agreed on. 'So there was a lot of interest' Hunstead said, 'in actually obtaining a complete set of redshifts for all of the galaxies in the 3rd Cambridge Catalogue.' The work was carried out as a collaborative effort between three institutions. Martin Ryle from Cambridge University did the radio observations while Hyron Spinrad from the University of California at Berkeley used the Lick telescope to carry out the spectroscopy measurements and Hunstead did the optical position measurements with his X-Y measuring machine. A Nobel Prize was awarded to Ryle a year later for his development of synthesis imaging.

One of the other ways of resolving the issue of whether there was a connection between radio galaxies and quasars was according to Hunstead, 'to find chance alignments between a background quasar and a foreground galaxy, in which you could then look at the spectrum and show that it was actually behind the galaxy.' From their observations of very weak calcium lines in the spectrum of QSO 0446-208 they were able to ascertain that the absorption was due to an intervening galaxy (Blades, et al. 1981). It was only the second example of such absorption that had been observed. The study of absorption lines allowed them to probe distant galaxies and as a result of this 'we were able to learn something about heavy elements that were present in those galaxies and it acted as a launching pad for our subsequent work in looking at element abundances in galaxies that happened to lie along the sight lines to distant quasars.'

His studies on QSO 2000-330 at $z = 3.78$ (Murdoch, et al. 1986) led to a reappraisal of much of the earlier work on quasars. There were claims that the number of absorption lines increased with redshift while others claimed that the numbers decreased or there was no change with redshift. His team was 'able to measure the density of Lyman-alpha lines in a very controlled way in this high redshift quasar at a redshift of 3.78, which was then the highest redshift quasar known, combined with the lowest redshift object, BL Lac object 0215+015. They gave us the lever arm that enabled us to determine the abundance or the density of these Lyman-alpha absorption lines unequivocally.' They used the 'maximum likelihood technique' to good effect. The technique is now 'used universally for exploring this process of evolution with redshift.'

In the process they also discovered something interesting. According to Hunstead, 'We discovered that the reason for the earlier discordant results was because the quasar itself was influencing its local environment and that the region around the quasar was being ionised by the quasar so that there were fewer clouds of neutral hydrogen around the quasar, so the number of absorption lines diminished as you

went towards the quasar. But if you looked away from there you indeed saw a very prominent increase with redshift.'

In the 1980s there was a realization amongst astronomers that there was a class of absorbers that could be seen against distant quasars. The column density of neutral hydrogen was so large that it actually blocked out the light of the quasar altogether over a range of wavelengths. By determining the hydrogen column density accurately it is possible to measure the strength of heavy element lines that are associated with that hydrogen. In this way one can make an abundance measurement. Abundance measurements are always made of the ratio of the element of interest to hydrogen. He chose two elements (zinc and chromium) to make abundance measurements. According to Hunstead, 'most of the elements that are produced in stars don't stay in the gas phase in the inter-stellar medium. They get attached to grains of dust and are basically depleted from the gas phase. So by measuring the gas phase abundance of an element like iron you're getting a very misleading impression of how much iron there is out there.' 'It turns out that one element, zinc', he continued, 'is hardly ever depleted on to dust grains and the abundance of zinc in different sight lines within the Milky Way galaxy towards hot clouds and cool clouds is more or less the same. And so zinc was not depleted on to dust grains. We don't understand why because the nucleosynthetic origin of zinc and iron are very similar. Zinc could then be used as a tracer of the heavier abundance at high redshift when it was used in conjunction with the Lyman-alpha line. It also happens that close to the zinc lines are chromium lines. Now chromium like iron is very heavily depleted on to dust and so by measuring the relevant abundances of both zinc and chromium you could determine the abundance of the heavy elements using the zinc abundance and you could learn how much dust there was by looking at the chromium abundance or the chromium to zinc ratio. (Pettini, et al. 1994)'.

Most astronomers had assumed that all quasar spectra were the same. That is, the spectrum obtained for a radio loud object and a radio quiet object looked very much the same. However, no one had actually generated composite spectra to study the question. Hunstead and Joanne Baker who had come down from Cambridge University to do her PhD discovered that 'the radio spectra were quite different depending on whether you had a quasar pointing towards you or with its jets in the plane of the sky. And all of them were different from another class of quasars called compact steep spectrum quasars and they in turn were different from the optically selected quasars.' This was the first example where a distinction was drawn between the radio loud and radio quiet objects (Baker & Hunstead 1995).

He is now leading an international team which is investigating how the first massive galaxies formed. This is a follow up, he said, 'of the work he had done on quasars.' One of the important features of quasar astronomy is that most of the light that is seen is coming from a very active nucleus which overwhelms the light from the host galaxy. According to Hunstead, 'In order to learn more about galaxy formation in the early universe you need to find radio galaxies where the light from this very bright nucleus is not pointing towards you but is pointing in the plane of the sky. It may be illuminating clouds laterally but not along the line of sight. So then you actually explore the building up of massive galaxies at early times because both quasars, radio loud quasars and radio galaxies have the same hosts basically, these giant elliptical galaxies.' For this project his team has to use various astronomy facilities such as the Molonglo Synthesis Telescope, the VLA, the Anglo-Australian Telescope, the European Southern Observatory and the eight metre Gemini telescope.

POSTGRADUATE STUDENTS

He has over the years supervised a number of PhD students who have gone on to lead productive astronomical careers. Some of these include John Reynolds who is currently the Director of the Parkes Radio Telescope, Vickki Meadows who is now at Caltech and is closely associated with the Spitzer telescope, Joanne Baker went on to a post-doctoral fellowship

at Cambridge University then won a Hubble Fellowship at Berkeley and is now Chief Editor in the UK for the planetary science section for Science magazine, Tanya Hill is the science communicator at the Melbourne Planetarium and Melanie Johnson-Hollett is a lecturer at the University of Tasmania.

Hunstead has a track record of highly cited publications and was recently recognised by being awarded the Australian Science Citation Laureate. His productivity he says is due to the fact that 'I am working on many projects. It has meant that I never become an expert in any one field but I have become a semi-expert in a whole lot of fields. That enables you to make connections between fields that you would not otherwise be able to do.' He works long hours. 'I usually come to work on Saturdays as well and sometimes on Sundays.'

As to his major achievements to date he said, 'I don't place a lot on the research that I've done, although I've enjoyed it. It's all been great fun. I get the biggest buzz from working with students and seeing them develop into researchers through to their PhDs and beyond.'

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Galaxies and the HI Survey

RAGBIR BHATHAL

Abstract

Lister Staveley-Smith is a Premier's Fellow at the University of Western Australia. He was appointed by the Western Australian government to ensure that the Square Kilometre Array (SKA), the largest radio telescope in the world will be built in Western Australia. To this end the Western Australian government has so far contributed $30 million towards the $2 billion SKA project. Staveley-Smith was previously the Assistant Director Astrophysics at the Australia Telescope National Facility in Sydney. He is an expert in the study of galaxies and the Magellanic Clouds. He was the driving force in the building of the highly innovative Parkes 21 centimetre multibeam receiver which has made several significant contributions in astrophysics.

Keywords: HI survey, Multibeam receiver, Square Kilometer Array

INTRODUCTION

Out of Africa? Not exactly! But Lister Staveley-Smith spent a number of his younger years in Africa, an exotic continent of huge national parks, large rivers, great water falls and Mount Kilimanjaro made famous by Ernest Hemingway in his classic short story *The Snows of Kilimanjaro*. It was in Africa that the Leakeys and others found the remains of our ancestors who walked the length and breadth of the ancient continent thousands of years ago to finally emerge out of Africa with octopus like tentacles to spread themselves over the whole of planet Earth.

Born in Edinburgh in the Sputnik era Staveley-Smith was the only child of a mother who was a public servant and a father who was an English teacher with an avid interest of science. 'My father was a very outgoing person. Though he didn't in any way have a science background or an analytic brain, he had a fascination for science which must have rubbed on me when I was growing up.' In fact, despite his non-science background his father started 'an astronomy club in school.' As a young boy Staveley-Smith played with Meccano sets in an era when Meccano sets were the thing most young boys played with before the advent of home computers. According to him, 'he was very much mechanically minded although at one stage one of my professional ambitions was being a veterinary surgeon.'

He found the Edinburgh museum 'a fascinating place to go to and I must have visited the science museum once a month or so. It was free and there were lots of buttons to press.' His interest in astronomy began when he was about twelve years of age. 'I developed an interest in astronomy mainly through reading about things astronomical from the National Library in Edinburgh. I certainly remember being influenced by science and even science fiction writings of people like Isaac Asimov and I've been very impressed by Fred Hoyle's book, *Frontiers of Astronomy*.'

He spent most of his secondary school years in Nairobi, Kenya. Lenana High School was a selective high school and many of its graduates 'went on to become leaders in Kenyan society', according to him. He was very interested in physics. He had some very good teachers in mathematics and science and they were 'directly responsible for his becoming interested in these subjects.' It was at this school that he assisted in building a 12 inch reflector and from the 'point of view of research I do now, we also built a small corner reflector radio telescope.'

CAMBRIDGE AND JODRELL BANK

He went up to Trinity College in Cambridge on an Exhibition and was rather pleasantly surprised to find out that it was also the College that the great physicist, Isaac Newton

had attended in the 17th century. He found Cambridge a little difficult to get used to in his first year but by his second and third years he grew to like it. He particularly enjoyed the experimental work at the Cavendish and remembers his 'tutorial sessions with Martin Rees', an accomplished English astronomer and a prolific writer of books and scholarly articles and other stimulating researchers. While at Cambridge Staveley-Smith was encouraged by his lecturers 'to pursue a research career.'

After graduating from Cambridge he moved on to do his PhD at Jodrell Bank under the supervision of Rod Davies, a former Australian who had gone to live in the UK. 'Davies', according to Staveley-Smith, 'had a broad range of interests from the study of the galaxy to the cosmic microwave background.' Staveley-Smith's PhD thesis was on mapping peculiar velocities in the local universe. His PhD thesis was more significant in what it did not find. At the time it was thought that 'nearby structures in the universe, supergalactic structures, clusters and superclusters were responsible for generating the gravitational forces that were accelerating our own Galaxy.' He could not reproduce the results found by other astronomers and he believes 'these accelerations are undoubtedly generated at further distances. And to this day it still remains unclear where the bulk of this acceleration comes from.' From Davies he picked up 'certain ways of dealing with research problems which are part of my research tools arsenal to this day', he continued. He spent the next few years on post-doctoral fellowships. In fact, during this time he developed 'a new acoustic optical spectrometer which provided order of magnitude more bandwidth than available with traditional devices. And it was actually very important in discovering an important hydroxyl maser in a very distant galaxy.'

TO AUSTRALIA AND THE ATNF

A UK Science and Engineering Research Council Bicentennial Fellowship to celebrate the Bicentenary of Australia enabled Staveley-Smith to move to Australia to join the Anglo-Australian Observatory (AAO) as an independent post-doctoral Fellow. It was an interesting time to be at the Anglo-Australian Observatory as new initiatives were being undertaken at that time. From there he moved on to the Australia Telescope National Facility (ATNF) as a post-doctoral fellowship before being offered a permanent job at the ATNF in 1995 and later being appointed as the Assistant Director and Head the Astrophysics Department. At the time he joined the ATNF it had a different research environment from the AAO. Construction of the Compact Array was sucking up the resources of the ATNF. There were budget overruns and there was not a lot of spare money for pure research. But, according to Staveley-Smith, 'That turned around as the Compact Array came on line and people could move from old style research with old style facilities to new more innovative research. New money was also injected at various stages through external contracts given to ATNF'. Under his leadership as the Head of Astrophysics the number of students in the mid-1990s increased from about a dozen to 'over 30 PhD students.' He is particularly proud 'of the people we've been able to bring into the ATNF.'

Staveley-Smith has a track record of producing papers with high citation rates. He has tackled a number of problems in the evolution and structure of galaxies and dwarf galaxies. He defined dwarf galaxies 'as galaxies that have a luminosity which is fainter than around one per cent of the luminosity of the Milky Way'. Dwarf galaxies are by far the most numerous objects in the extragalactic Universe. Some 80 per cent of the known Local Group galaxies are dwarfs, and the space density of dwarfs may be a couple of orders of magnitude higher than that of bright galaxies. He believes there are 'quite a few problems that relate to the formation of dwarf galaxies and their overall role in the formation process of galaxies. For example, do hydrogen rich dwarf galaxies become the dwarf elliptical galaxies that are known to surround the Milky Way in great numbers? Do blue compact dwarf galaxies evolve into low surface brightness galaxies and vice versa? How do dwarf irregular galaxies manage to sustain ongoing star formation over such long time scales? Many of these

objects are still quietly forming stars, 14 billion years after the big bang.' Overall dwarf galaxies are very important in cosmology, however, they are still the poor cousins of normal galaxies according to Staveley-Smith.

In their study of HI and the optical observation of dwarf galaxies (Staveley-Smith, et al. 1992) they were 'able to derive a good estimate of the rotation velocities and if you base the size on the optical size of the galaxies it turns out you got quite a good estimate of the dark content without knowing exactly how far the hydrogen extended. But even the extent of the hydrogen is little indication of how far out the dark matter itself actually stretches'. Since his early studies of dwarf galaxies a number of studies have been done and are still being done, particularly 'in examining the role of dark matter in dwarf galaxies.'

In outback Australia the Large and Small Magellanic Clouds (LMC and SMC) can be seen as two fuzzy patches in the night sky. They are important satellite galaxies of the Milky Way. They are not quite the closest anymore as we now know of closer objects, such as the Sagittarius Dwarf Elliptical Galaxy. The LMC and the SMC are great laboratories for astronomers particularly because they lie well above the obscuring plane of our own galaxy. They are tremendous laboratories for the study of galaxies both on a global scale and on a very detailed scale for studying the interactions of individual star-forming regions with the interstellar medium and on a grand scale of things their interaction with each other and our own Galaxy. This interaction has not only been important for the past evolution but also the future evolution of the Milky Way and the Magellanic Clouds.

The survey of neutral hydrogen emission in the Small Magellanic Cloud with the Australia Telescope Compact Array (Staveley-Smith, et al. 1997) was an important milestone for Staveley-Smith. 'This was a particularly interesting study for me because it was of great astronomical importance of having the compact array available in the Southern Hemisphere. We did not have anything like the Very Large Array to study the SMC previously. The SMC has always been the poor brother of the LMC as far as attention by astronomers is concerned.' The study was also important to Staveley-Smith. 'It was a huge technical challenge in its time because of various telescope related and software related issues. And because I was at a national facility I felt it was my duty to pursue this and fortunately I was able to bring together a very competent team of people to pursue this. It was also significant because it was a stepping stone to the study of the LMC.'

They found that the spatial power spectrum relation (Stanimirovic, et al. 1999) followed a similar pattern as that found in our Galaxy by other astronomers. Their study emphasized to them 'that there was an input of energy into the SMC at many size scales, from the very large scale gravitational interaction with its neighbours, to the smaller spatial scale where winds from stars and the mechanical output from supernova was able to drive bubbles into the interstellar medium'. This it seemed to them to lead in the SMC to a hierarchy of structure which is 'more akin to turbulence than anything else'. In those days turbulence was not seen as being relevant by astronomers. The emphasis was on a static two-phase or three-phase interstellar medium in hydrostatic equilibrium. According to Staveley-Smith, 'These days turbulence is taken very much more seriously and astronomers have the computational tools to study star formation in turbulent environments and turbulence is regarded as an important star formation mechanism in itself.'

His work on an HI aperture synthesis mosaic of the LMC (Kim, et al. 1998) provided some rather surprising results. On a large scale they were surprised by the overall regularity of the LMC and neutral hydrogen. 'Especially', he said, 'when compared with the almost scruffy irregular appearance of the LMC in optical photographs. And also with the SMC we were surprised by the number of massive shells of gas which were present.' 'The shells', he said, 'tell of recent star formation.' 'And that recent star formation stretches from say about one million years to a hundred million years. They have given us a useful indicator of the average state of the LMC in the period which immediately

follows the encounter with the SMC. That encounter probably occurred about 200 million years ago, so as well as the LMC having a direct effect on the formation structure and tearing apart of the SMC, vice-versa is true as well. That interaction had some effect on the LMC. We by no means understand that fully'.

According to Staveley-Smith, 'There are still raging arguments about the effect of various compression waves on the star formation in various parts of the LMC'.

MULTIBEAM AND THE ALL SKY HI SURVEY

Staveley-Smith was the driving force behind the building of the highly innovative Parkes 21 centimetre multibeam receiver (Staveley-Smith, et al. 1996) and the HIPASS survey which was one of the largest and deepest HI surveys undertaken in the southern sky. It was a blind survey of the whole sky south of Declination 25° in the velocity range -1200 km/s < cz < 127000 km/s. It was also a period when he began to write papers with a large number of astronomers. Because of the scale of the instrument there was a sharing of its development with astronomers from the UK. The reason for this according to Staveley-Smith was 'that they had skills that we didn't have with low noise amplifiers and we had skills that they didn't have.' He was also interested in surveys as a means of tackling fundamental problems."

He had initially talked about the multibeam project with Alan Wright at Parkes on several occasions. Later on Wright and Raymond Haynes 'dreamed up a multi-beam project for the small MOPRA telescope'. The MOPRA is a 22 metre dish close to the Anglo-Australian Telescope site. This telescope can be used either for stand-alone observations at millimetre wavelengths or as a component telescope of the Australia Telescope Long Baseline Array. But this was a non-starter because of the engineering and scientific limitations of the project. Staveley-Smith took over the role of project scientist from Haynes and 'following a nod from the engineering team and approved by Ron Ekers' (then Director of the ATNF), he changed it from a three by three array into a 13 beam double hexagon array. For its time the massive array was a great challenge and a great leap forward. The main reason for the change was according to Staveley-Smith, 'the availability of cheap correlators. A correlator is the back end spectrometer of the array. And an instrument like this required a correlator that was as powerful as the existing Compact Array correlator which was hugely expensive. And also the quality of a number of the engineering teams at ATNF, principally those led by Warwick Wilson, Mal Sinclair and Trevor Bird. And in such a multi-disciplinary team it was just possible to not only think about a project like this but to do it.'

The multibeam instrument had several advantages in comparison with other telescope systems worldwide. According to Staveley-Smith, 'The massive field of view of the multibeam and the more or less uncompromised sensitivity made it a very fast instrument and the fastest such instrument for the better half of the decade I believe. At the time many senior people in other institutes held the view that single pixel receivers and single feed receivers would always be better because they could always be optimized in some way. But I think those views were blown out of the water as soon as we made the first sky measurement with the multi-beam instrument at Parkes because we took an uncompromised attitude to the sensitivity and made sure nothing diminished its ability to do a sensitive HI survey at 21 centimetres'.

With this instrument astronomers were able to undertake qualitatively different science from what had been done before. 'It wasn't more of the same more quickly but it was different scales of problems. Not just looking at individual galaxies anymore but looking at the whole sky at depths which are really quite interesting', he said.

The All Sky HI Survey was a tremendous success. One of the early papers that made the headlines was the investigation of the tidal disruption of the Magellanic Clouds by the Milky Way (Putman, et al. 1998). They discovered a leading tidal arm of the Magellanic system.

According to Staveley-Smith, 'This was a fantastic indication that the tidal forces, not just ram pressure forces were responsible for shaping the overall Magellanic system. And that implies that our own Milky Way galaxy must possess a very extensive dark matter halo because that's the only way that such features can be produced in models.' The project also enabled them to make a number of advances in instrumental and imaging techniques (Barnes, et al. 2001). 'One of them', Staveley-Smith said, 'was the ability to handle interference in a robust way. We developed a procedure that was able to without much intervention to produce final images and final data cubes which were mainly free of the effect of radio frequency interference which at these frequencies is all pervasive from PCs, printers, aeroplanes, mobile phones, satellites, et cetera.'

The 'Mass Function' is in many ways similar to the luminosity function which is used in optical astronomy. In many ways it is more fundamental than the luminosity function because mass is in general a more fundamental quantity. It is also a more useful term from a cosmological perspective. In their study of 1000 brightest HIPASS galaxies (Zwaan, et al. 2003, Koribalski, et al. 2004) team members were able to provide the first accurate measurement of the Mass Function. According to him, 'Previous surveys were of a few dozen galaxies and really open to all sorts of wild interpretations. So this for the first time gave us accurate Mass Function over a reasonable range of HI masses and it enabled us to divide that Mass Function into different classes of galaxies and the different density of types of galaxies.' The large sample of galaxies also enabled them to give an accurate measurement of the cosmological mass density of neutral gas: $\Omega_{\rm HI} = (3.8 \pm 0.6) \times 10^{-4}\,{\rm h}_{75}^{-1}$. They found that low surface brightness galaxies contributed only 15% to this value which was consistent with previous findings.

SQUARE KILOMETRE ARRAY

In 2004 the Western Australian government appointed Staveley-Smith and Peter Quinn as Premier's Fellows at the University of Western Australia to ensure that the Square Kilometre Array (SKA), the world's largest radio telescope would be built in Western Australia. The Western Australian and the Australian governments are currently contributing \$30 million and \$118.5 million respectively to help meet some of the key technology and engineering development requirements of the \$2 billion international SKA project.

The SKA is an ambitious project and if all goes well it will be completed in about 2020. At the moment South Africa and Australia are in the running. As for the funding, Staveley-Smith, said, 'The expectation is that Europe might put about a third of the funding, North America might put a third of the funding and the rest of the world will put in a third of the funding. The partners currently are many European countries, USA, Australia, Canada, China, Argentina, India, New Zealand, South Africa and Russia.' The SKA will have 'a collecting area of some 300 times larger than that of the Parkes telescope and around 20 times larger than the largest array in existence today.' The candidate site is in the shire of Murchison in Western Australia at a station called Boolardy Station about 300 km by road from Geraldton in a very radio quiet area.

There are a number of science goals that astronomers hope to achieve with the SKA. According to Staveley-Smith, 'one of the main headline goals of the SKA when the concept was first mooted was the ability to make HI maps of large spiral galaxies at redshift three. So it's through the HI line that galaxies will be mapped at high redshifts and it's through the HI line that we will be mapping the structure of the universe in this epoch of re-ionization because it's the balance between neutral gas and the ionized gas that is a sign of this re-ionization.' They will also be imaging galaxies at high redshift, testing Einstein's theory of general relativity in extreme environments around pulsars and studying the evolution of magnetic fields in the universe.

Is he expecting any surprises? He said, 'It's a telescope that is designed to be a facility for many decades. And undoubtedly in that time there will be many surprises. I personally think we might have quite a few surprises in the so-

called study of the transient universe. That is objects switching on and off which have been tremendously exciting at other wavelengths, such as in the gamma-ray bands in recent years.'

Of his major achievements to date, Staveley-Smith said, 'I have taken a lot of pride throughout my research career in helping others in their research achievements and helping students and post-docs achieve what they wanted. As well as my own achievements I take pride in the achievements of others I have been associated with'.

ACKNOWLEDGEMENTS

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For the latest developments on the SKA refer to `http://www.skatelescope.org`

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The Clarke Medal 2008

PROFESSOR BRADLEY POTTS

Professor Bradley Potts at the Award Presentation.

The Clarke Medal is awarded for outstanding research in the natural sciences in Australia, and rotates between botany, zoology and geology. The medal commemorates the Rev W.B. Clarke who played a key role in the Society in the middle and later part of the 19th Century. This year's award is in Botany, and the winner is Professor Bradley Potts of the University of Tasmania.

Professor Potts is renowned for his work on eucalypts and virtually all his career has been devoted to the study of these iconic trees. He is one of the most the most published scientist worldwide on eucalypts. His work has encompassed diverse studies from their quantitative and molecular genetics, to their evolutionary and reproductive biology.

Most of his career has been spent at the University of Tasmania, where he is now Professor in Forest Genetics.

He has established a major program in eucalypt genetics, and his group has published one of the earliest papers on eucalypt DNA variation and the largest study on eucalypt phylogeny using DNA markers. His earlier work was on understanding the evolutionary response of eucalypt population to changing environments, including invasion by hybridization. He has subsequently used molecular information to determine the role that hybridisation has played in the evolution of the genus as well as determine the historical migration routes of eucalypt species. His research group has been a leader in assessing the risk of gene flow between plantation and native eucalypts as well as characterising the eucalypt genetic resources of the island of Tasmania for conservation purposes.

He is also active in applied research. His group provide extensive research to back the breeding of eucalypts both nationally and internationally, particularly the Tasmanian blue gum, which is now a model species for eucalypt genetic research. He has continuously led genetic research in three consecutive forestry Cooperative Research Centres since 1991. He has also contributed to the initiation of an international project to sequence the entire genome of a eucalypt species. This USA based project is expected to be completed next year.

With collaborators he produced some of the first studies in the emerging field of community and ecosystem genetics, a field which links genetics and ecology. These studies examined the impact that genetic variation in eucalypt species has on interacting organisms, such as fungi, insects and marsupials; work which has led to invitations to publish in prestigious journals such as Science and Nature Reviews Genetics.

Professor Potts is clearly a deserving recipient of the Clarke Medal.

Edgeworth David Medal 2008

ADAM MICOLICH

Dr Adam Micolich at the Award Presentation.

Adam Micolich is an outstanding young physicist whose High Distinction level undergraduate studies culminated in the award of the UNSW Medal in Physics. He has an impressive record of publications in first class journals such as Nature, Physical Review Letters, Physical Review and Physics World which have been extensively cited. His work is internationally recognised, as evidenced by numerous invited papers at international conferences.

In 2006 he was awarded a Young Tall Poppy award by the Australian Institute of Policy and Science for his contributions to Australian physics research. In 2003, he was awarded an ARC Australian Postdoctoral Fellowship to work on plastic electronics. He discovered superconductivity in ion-implanted plastic films, which was the first observation of a true zero resistance state in a plastic-superconductor hybrid material. This is potentially of very significant technical interest, with the present world wide interest in using plastics for the next generation of electronic devices.

The field of mesoscopic semiconductor device physics in which Adam Micolich works involves the electronic properties of semiconductor devices with feature sizes larger than atoms, but well below the size of bulk matter. The phenomena and mechanisms in the mesoscopic regime are governed by quantum mechanics but bordering on the classical regime. There are numerous physical, chemical and biological problems in this shadowy region which are only now yielding to new experimental techniques. He has demonstrated that he has the ability to thrive in this difficult and expensive terrain and has been able to attract millions of dollars in grants to remain internationally competitive.

As one example, his Quantum Electronic Devices Group has developing hole quantum wires. This work has been published in a number of high-impact papers in Physical Review Letters and Applied Physics Letters. He is currently working on the development of hole billiard devices where spins can be manipulated via their interaction with the billiard geometry, creating the equivalent of spin-optic devices such as prisms and lenses. These developments are again at the leading edge of the field, from both a basic science and from a technological point of view.

He played a key role in developing the fractal mathematical techniques involved in analyzing Pollock's famous drip-paintings. Published in Nature, this work was widely reported in the scientific and art literature and in the general media, including The New York Times, The Guardian and New Scientist. He has shown considerable ability in presenting advanced science to the general public through numerous popular communications.

Both in his specific discoveries in mesoscopic physics and his ability to make significant contributions to a wide range of challenging problems Adam Micolich has shown himself to be a worthy winner of the Edgeworth David Medal.

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Scholarship Prize 2008

The Council of the Royal Society of NSW funds the Royal Society of New South Wales Scholarships in order to acknowledge outstanding achievements by young researchers. Applications are considered from PhD candidates, enrolled in a university within New South Wales, who have completed at least two years of candidature by 30 April. There is no restriction with respect to field of study within the sciences and up to three Scholarships will be awarded each year. Applicants must be Australian citizens or permanent residents of Australia.

GERARD KAIKO
OUTSTANDING ASTHMA RESEARCHER

The Royal Society of NSW has awarded the Scholarship Prize for 2008 to University of Newcastle PhD student, Gerard Kaiko, for his research into the link between a viral infection that is the most common cause of upper respiratory tract infection in infants and the increased risk of asthma in later childhood.

The virus, Respiratory Syncytial Virus (RSV), is typically associated with the diagnosis of bronchiolitis and severe infections have long been associated with the development of asthma. Gerard has found that a particular type of lymphocyte, the natural killer or NK cell, is essential for a normal immune response to the RSV. The depletion of NK cells prior to RSV infection in mice gave an immune response that displayed several features characteristic of asthma. These included increased mucus in the airways and an increase of a particular type of white blood cell, eosinophils, commonly associated with asthma. In mice lacking NK cells, there was an increase in the production of the types of antibodies and cytokines that are present during asthma attacks. Gerard writes: 'this study suggests a novel mechanism to explain the association between severe RSV infection and asthma.'

There is little doubt that Gerard Kaiko's exemplary student record will be the vanguard to a highly successful future. He is undertaking his studies for a PhD in the Centre for Asthma and Respiratory Diseases in the University of Newcastle, where he graduated with First Class Honours in his Bachelor of Biomedical Science degree and was awarded the University Medal in 2006. He already has an impressive list of full journal publications as well as other prizes and awards.

The Royal Society of NSW is proud to award the Scholarship to a student whose work has the potential to lead to an understanding of the cause of asthma and perhaps to a new approach to its treatment.

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Notes

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Three, single sided, typed copies of the manuscript (double spacing) should be submitted on A4 paper.

Spelling should conform with 'The Concise Oxford Dictionary' or 'The Macquarie Dictionary'. The Systéme International d'Unites (SI) is to be used, with the abbreviations and symbols set out in Australian Standard AS1000.

All stratigraphic names must conform with the International Stratigraphic Guide and new names must first be cleared with the Central Register of Australian Stratigraphic Names, Australian Geological Survey Organisation, Canberra, ACT 2601, Australia. The codes of Botanical and Zoological Nomenclature must also be adhered to as neccessary.

The Abstract should be brief and informative.

Tables and Illustrations should be in the form and size intended for insertion in the master manuscript – 150 mm x 200 mm. If this is not readily possible then an indication of the required reduction (such as 'reduce to 1/2 size') must be clearly stated. Tables and illustrations should be numbered consecutively with Arabic numerals in a single sequence and each must have a caption.

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Maps, diagrams and graphs should generally not be larger than a single page. However, larger figures may be split and printed across two opposite pages. The scale of maps or diagrams must be given in bar form.

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